UNIVERSIDAD CARLOS III DE MADRID
AND
UNIVERSITÀ DEGLI STUDI DI PERUGIA

Optimization of a planar photovoltaic concentrator prototype

Energetic Engineering Department

UNDERGRADUATE THESIS PROJECT

AUTHOR: LETICIA VALENCIA BLANCO

DIRECTORS: FEDERICO ROSSI

BEATRICE CASTELLANI

To my parents

ABSTRACT

There is a need to accelerate the development of advanced clean energy technologies in order to address the global challenges of energy security, climate change and sustainable development. This challenge was acknowledged by the Ministers from G8 countries, China, India and South Korea, in their meeting in June 2008, where they declared the wish to prepare roadmaps to advance innovative energy technology.

Solar energy is the most abundant resource on the earth. The solar energy that hits the earth's surface in one hour is the same as the amount consumed by all human activities in a year. Direct conversion of sunlight into electricity in PV cells is one of the main solar active technologies, the two others being concentrating solar power (CSP) and solar thermal collectors for heating and cooling. Today, PV provides 0.1% [12] of the total global electricity generation. However, PV is expanding very rapidly due to the dramatic cost reduction. PV is commercially and reliable technology with a potential growth all over the world. PV is projected to provide 5% of global electricity consumption in2030, rising 11% in 2050 [12]

Achieving this level of PV electricity supply will require more concerted policy support. Sustained, effective and adaptive incentive schemes are needed to help bridge the gap to PV competitiveness, along with a long-term focus of PV technologies, including commercially available systems and emerging and novel technologies.

This work is a part of an innovative project in which a research about photovoltaic low concentration is being developed. Both, theoretical studies and practical testing are carried out. Theoretical because of the development of a mathematical model for the prototype and practical testing with electronic tools directly from the pilot facility.

The basic aim of this study is to analyse the possible reasons of energy losses at the prototype, primarily due to geometrical factors, that is to say, because of the design of itself. Once it has been analysed, a more optimum configuration will be proposed in order to achieve and improvement in the efficiency.

CONTENTS

Chapter 1

1. INTRODUCTION AND OBJECTIVES

In the beginning of the 21^{st} century, the renewable energies consumption still represented a minority part of the total world energy consumption. However, especially due to the harmful emissions and climate change, the situation is drastically changing in many countries. Expectations are that renewables will play a major role by the end of this century. [1] This chapter is an introduction to the topic. It talks about the current situation of the world energy resources and consumption, how the energy problem is being treated and what are the existing technologies.

1.1. Introduction

The civilization, in the way we know it nowadays, depends extremely on the huge amount of energy produced (around 320 TW/day) that comes mainly from fossil fuels. While this consumption remains the same, without modifying essentially the civilization concept, it is necessary to change the typology of sources used in order not to meet a highly energetic dependant situation from the countries that control oil fields. In long term, the world wide availability of fossil fuel will arrive to an important reduction driving to tense political relations. Besides, to all of this, it should be added the effect of the CO_2 emissions to the atmosphere and to the global life quality. [3]

The present energy situation is not sustainable as fossil fuel reserves are diminishing and will not be able to satisfy the increasing demand associated with economic development and population increase. In 2005, the world oil consumption was equal to 85 millions of barrels per day. This represents an average of one Olympic-size swimming pool every 15 seconds or 5500 pools during the day. [4] The population of the world will keep growing and it is expected to stabilize around 9 billion (nowadays is around 6.8 billions)[5] . If all 9 billion people were expected to consume the same per capita amount of energy as industrialized countries today, we would need a factor of 20 times more than we do now. From now on, it is needed to set a useful target because it takes a long time to harness new technologies profitability and to change habits globally. During this period, increasing energy efficiency will affect our needs. Developing countries will need a deeper dedication to catch up the energy needs; and regretfully, some of them never will. On the other hand, the developed countries will reduce their wasteful energy habits. [2]

But, there is no doubts about we will need much more energy than now. If poor parts of the world roughly reach the average a factor of 2 o 3 more energy will be required. Furthermore, additional energy needs are likely to appear, for example, meeting future water necessities, say, desalination.

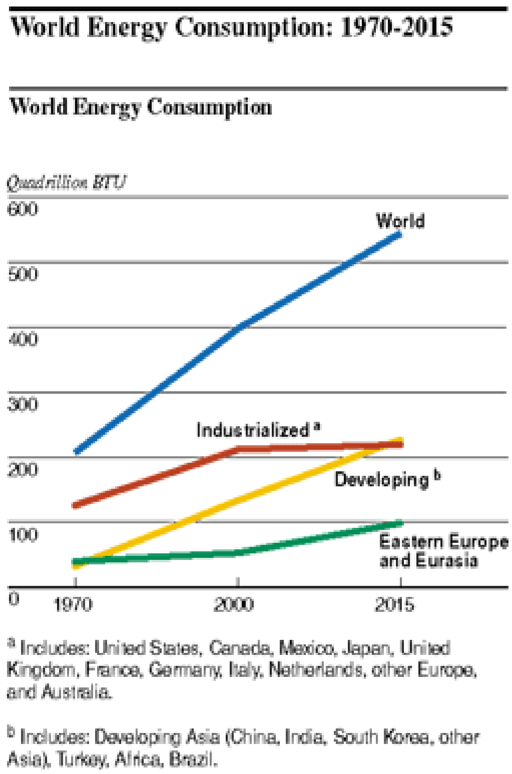


Figure 1 Evolution of the World Energy consumption 1970-2015 [6]

In Figure 1, it is shown the possible evolution of the World energy consumption, but if we think about a further future, keeping the tendency of growth, it can asked, where is the energy going to come from? It cannot be all from oil because oil wells will slowly dry up. It should be also considered the increase in oil price that has damaged the economies and the developing countries. This is only the prediction of tougher times to come, both economically and politically.[2] It will not come from fission energy either, because uranium is also a limited resource. Besides, fusion technology will not be developed at least in 40 years from now.

The renewable way of the energy, in all of its modes, becomes, not only by an ethic necessity but by a strategic necessity, whose importance will be evident in the next 20 years.[3] Renewable energies are key players regarding world energy supply security and the reduction of fossil fuel dependency and harmful emissions to the environment.[1] Considerable developments have been achieved on renewable energies, especially in Western Europe.

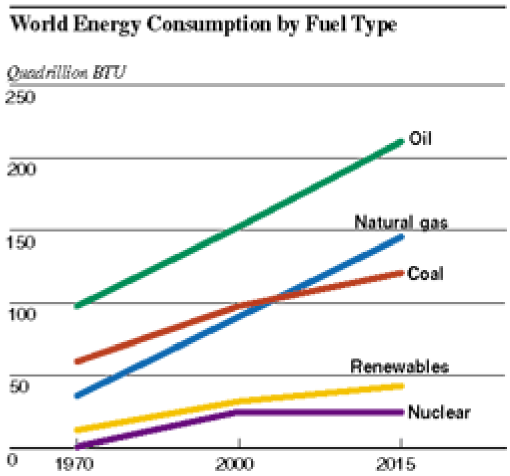


Figure 2 World Energy Consumption classified by fuel type 1970-2015 [6]

In summary, looking towards the horizon, oil will become less available and coal will not able to be used without a significant damage to the environment, fusion will have no function, hydrogen will remain marginal, and nuclear fission can be expected to increase lightly. Renewables will not able to fill the whole vacuum because of fossil fuels but they will play the main role.

1.2. Approach

This work is a part of a project, carried out between the enterprises IPASS Scarl and Metalmeccanica Pulsoni, in which it is combined experimental and computational calculations in a planar low-concentrated photovoltaic prototype. Particularly, this study is carried out in collaboration with the work developed by Beatrice Castellani on her Research Doctorate Course.

The first approach of the geometrical configuration was already done before this project started. The construction of the prototype was performed by Pulsoni in whose installations it is placed.

'Prototype 0' design was done by a model built in Matlab environment and made by flat mirrors which constitute a low-concentrated photovoltaic prototype. The photovoltaic panel is made of monocrystalline silicon and the movement of the mirrors, in order to follow the sun movement is run by asynchronous motors.

Experimental data was taken from the prototype in order to determine the best cooling system since the increase in temperature drops off the efficiency of the PV panel. Besides, theoretical model was also developed to check this behaviour, resulting from them that the best option was the natural convection with a finned surface.

The specific task addressed by this present work is the evaluation of the possible reasons that does not allow the prototype to achieve higher values of concentration primarily due to the geometrical configuration. A geometrical solution to lower losses of reflected rays due to one-axis rotation of the mirrors will be also investigated. By this study, a new possible configuration will be proposed, 'Prototype 1' in order to improve the efficiency values.

1.3. Objectives

The main objective of this present work is to develop a numerical code to simulate all the situations along the year in which the concentrator will be exposed to varying the variables that may change its efficiency. The evaluation of all the possibilities will help to modify the geometry of the prototype in the sense of improving the total power produced. Moreover, in addition to the development of the code, a geometrical approach was done in order to verify that the mathematical model was correct.

In computational studies what matters are the accuracy and the computational cost of the code but, since this work is not about just developing a program but the results it provides and its meaning, the project will not be focused on this aim. Mainly, this work is about developing a code for the total power of the system by using Matlab R2007b. Besides, the mathematical model of the geometry was checked by means of AutoCAD 2008. The specific tasks that were performed in this present thesis were:

- By means of Autocad 2008, obtaining the conversion ratios of the concentrator for four sample days of the year, the solstices and the equinoxes, for different hours of the day.
- Development of a program in Matlab in which the conversion ratios were also implemented for every day of the year in step of 15 minutes.
- Comparison of the ratios obtained by both methods for the four days analysed and checking the mathematical model.
- Improvement of the Matlab code performing the total energy that the concentrator is able to achieve.
- Variation of the variables, primarily the geometrical ones, to realize how the total energy varies and understand how it can be improved.
- Evaluation of losses due to the shadows between the mirrors, geometrically by AutoCAD and then by Matlab, introducing the mathematical model obtained; in order to define the effect of shadows on the mirror movement model. The results of the

analysis will allow calculating a corrective angle for mirrors' rotation in case that the reflected rays, because of shadows between two adjacent mirrors, don't hit the panel.

- Investigation on the possible horizontal movement of the panel during the year in order to improve the concentration efficiency through the recovery of reflected rays, otherwise lost because of the one-axis rotation.

In order to keep improving the system future works should be focused on:

- Geometrical improvement in order to reduce as much as possible the losses due to the prototype configuration.
- Extend the Matlab implementation to the shadows losses calculation.

Further details of the possible future works will be explained in section 5.2.

1.4. Contents

This work is divided in five chapters, going from general knowledge about the energy and the solar energy to the main aim of the project, evaluation of the efficiency of the pilot facility.

The first chapter presents a general description and motivation of the project. A brief introduction shows the importance of the problem to deal with and its practical application. The general approach to face the problem is introduced, and the particular aim of this project is placed in this general approach.

Chapter 2 presents a qualitative description of the sun as the source of all renewable energy. Basic features of the solar radiation and energy are explained to show then, the operation of photovoltaic cells. Finally, the principles of photovoltaic concentrators are shown in order to understand better the main problem.

Chapter 3 focuses its attention in the planar concentrator prototype itself. In it, it is explained the installation features and components that make up the facility. Then, the previous design of the prototype, how it was done and how it was implemented is explained. The main problems found before starting this study are presented and the results obtained from testing periods.

Chapter 4 is the core of the project in which all the development of the project is based on. In these pages all the results coming from almost six months of work are gathered. The evaluation of losses of the prototype, coming primarily from the geometrical design, is explained in this part of the document. All graphical studies and the computational ones are analysed. Besides, a comparison between the facility and a flat installation with the same surface will be carried out.

In last chapter, the fifth, the obtained conclusions are summarized and future researching lines are proposed.

Chapter 2

2. THE SUN

The Sun is the closest star from the Earth and it is its primary source of energy because of the thermonuclear chain reactions that take place on its surface. The solar energy (the radiant energy coming from the Sun surface arrives to the Earth as electromagnetic energy) is almost the only energetic way of influencing the atmospheric movements and terrestrial climate.

The Sun is an spherical, totally gaseous body, composed by 70% of hydrogen, 29% of helium and the spare 1% of other elements such us oxygen, carbon, magnesium, sodium, calcium, iron...[9]

2.1. The sun and the solar radiation

The spectral distribution at the external part of the terrestrial atmosphere is very important in applications such as the photovoltaic system of satellites. Instead of the spectral distribution that arrives to the terrestrial surface, which is not only a function of the extraterrestrial spectral distribution but also of the atmospheric composition of the Earth, results very important in many photovoltaic applications, thermal solar, photosynthesis, photochemical processes, etc.

The solar constant, which is the mean irradiated energy from the Sun per unit time and unit of area of an orthogonal surface outside the Earth's atmosphere at the mean distance between the Sun and the Earth; is around 1367 W/m^2. Sunlight on the surface of Earth is attenuated by the atmosphere so; less amount of power arrives – around 1000 W/m^2 with clear sky conditions and when Sun is at zenith.[10]

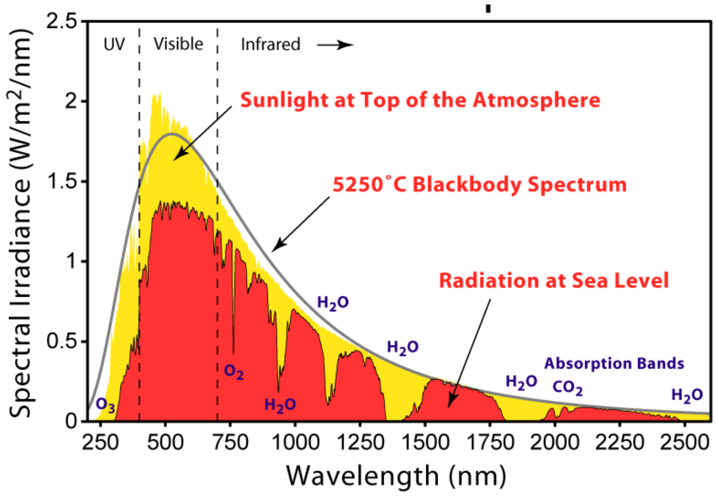


Figure 3 The solar spectrum.[11]

Now, the temperature of the Sun can be easily calculated by the Steffan-Boltzmann law, knowing that the total radiant flux over the external surface of the Sun is:

Equation 1

Where is the distance Sun-Earth and R is the radio of the Sun.

So, with Stefan-Boltzmann law, it is arrived to the Sun temperature:

Equation 2

Where is Stefan-Boltzmann's constant.

Solar energy is the most abundant energy resource on earth. The solar energy that hits the earth's surface in one hour is the same as the amount consumed by all human activities in a year.[12]

Besides, the solar radiation flux that arrives to the surface of the earth is the primary source of all ways of energy known. The solar radiation is the origin of the circulation movements in the atmosphere and oceans, the vegetable life or the fossil fuels, among others.

The most important features of the radiation are:

- Wide dispersion and therefore, low density.
- Intermittence and time variability.

These two are the fundamental characteristics to take into account when making the most of the energy coming from the sun. From the point of view of solar energy applications, it is useful quantify the amount of energy coming from the sun that arrives to the surface of the earth, and the relation with geographical and climatological parameters.

The amount of energy irradiated by the Sun per unit time can be calculated by the multiplication of the solar constant by the surface of a sphere with the same radio as the distance Sun-Earth:

Equation 3

Then, the incident solar energy at the terrestrial surface is equal to . If we take into consideration that around 70% of this energy is intercepted by the oceans, the annual incident energy to the ground is around , that is already a high value, enough to overcome the world energetic needs.

2.2. Sun- Earth interaction

The Earth rotates around the Sun describing an elliptic orbit, with the Sun positioned in one of its two focuses.

The eccentricity of the terrestrial orbit is very small, so that it can be considered an orbit similar to a circumference. In fact, the minimum distance between the Earth and the Sun, the *perihelion*, and the maximum, the *aphelion*, have the following values:

Equation 4

Equation 5

Where is the mean distance between the Sun and the Earth and, e is the eccentricity of the orbit.

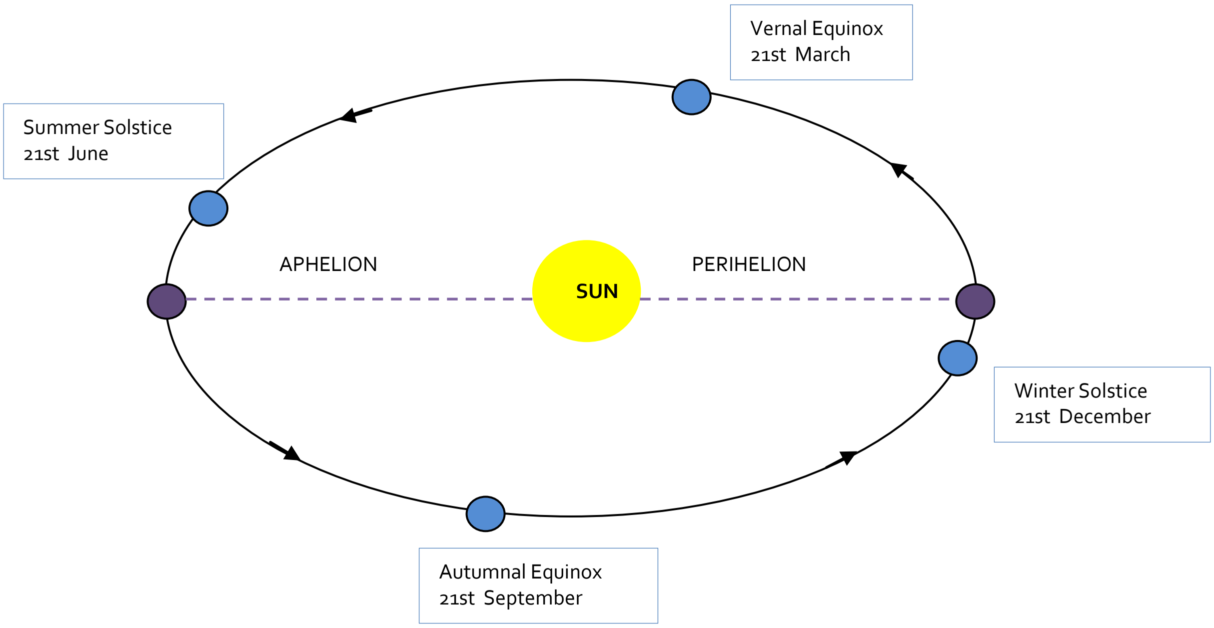


Figure 4 Motion of the Earth around the Sun

It is well known that the Earth has two rotational movements; one around an axis that passes through the poles, called polar axis, its duration is 24 hours; and another of translation around the sun describing the elliptic orbit, Figure 4, previously explained. The complete translation lasts 365 days 5hours 48 minutes and 46 seconds with a speed of 29.8 km/s. The polar axis has an inclination of 23.45º with the axis of the ecliptic, called obliquity of the ecliptic. This leads to different periods along the year, known as seasons. The obliquity of the ecliptic explains, first, the different heating of the Earth varying the position along the orbit and, on the other hand, the difference in day and night length throughout the year.

The solar radiation that arrives to the Earth is conditioned by to phenomena:

- Astronomical factors: are those that depend on the Sun-Earth geometry. Those agents are function of the relative position Earth-Sun and the geographical coordinates of the considered place (latitude and longitude). Those factors condition the route of the radiation though the atmosphere and the incident angle of the sun rays and as a function of the solar height at all times.
- Climatic factors: for each solar height, the maximum theoretical radiation that is expected at each place, does not generally take this value. There are several agents called climatic that attenuate the radiation that hits the terrestrial surface. The clouds, the amount of water steam, ozone, aerosol… in the atmosphere are responsible of this attenuation, which takes place mainly by absorption, reflexion and diffusion of the radiation.

The total radiation coming from the Sun that hits the Earth surface is composed by:

- Direct radiation, B: the one that arrives to the Earth directly from the Sun.

- Diffuse radiation, D: caused by the dispersion effects of the atmospheric compounds, including clouds.
- Reflected radiation, R: incident radiation at the surface that comes from the reflection with the ground. The coefficient between the reflected and the incident radiation is called albedo.

The global o total radiation, G, which arrives to a surface, can be expressed as the addition of the three components:

Equation 6

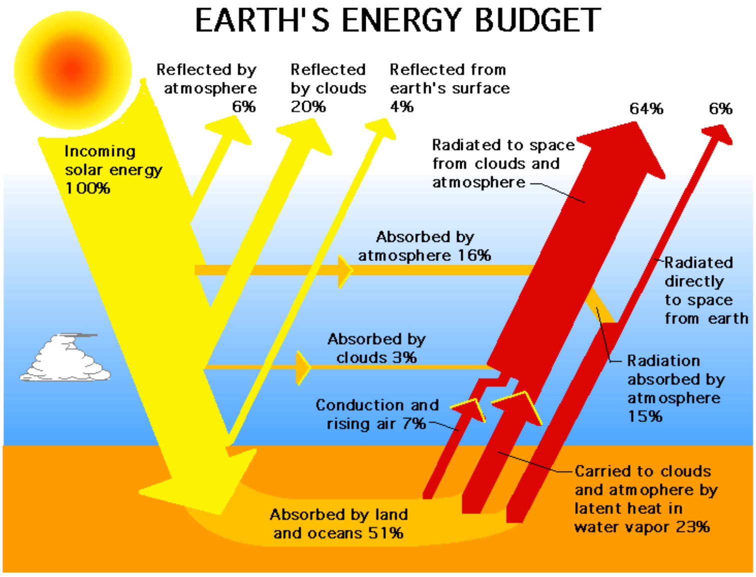


Figure 5 Earth's energy budget [13]

2.3. Solar equations

For an observer, looking at the sky from the Earth, the Sun's path across the sky takes the form of an arc that varies both during the course of the year and with the latitude of the place.

The apparent Sun route around the Earth is denominated ecliptic, therefore the revolution plane of the Earth around the Sun is called ecliptic plane, as mention before.

2.3.1. Solar declination

The angle between the polar axis and the normal to the plane of the solar radiation remains constant and also, the angle formed by the equatorial plane and the ecliptic plane.

Instead, the angle formed by the union of the centres of the Earth and the Sun with the equatorial plane, varies daily; or more accurately instantaneously. This angle is called *solar declination* and it is defined as the angle that the direction of solar rays form at midday, at the considered meridian, with the equatorial plane. It results also the same as the angle that the solar rays form at midday with the direction of the zenith over the equator and matches also with the geographic latitude at which one day of the year the Sun at midday is at zenith. It takes positive values when the Sun is above the equatorial plane and it is negative when it is below. [9]

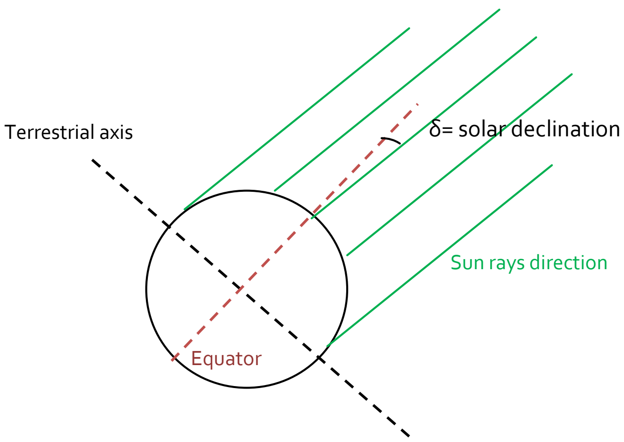


Figure 6 Definition of solar declination [9]

It takes a null value at the autumnal and vernal equinox, and takes a value close to +23.5º at the summer solstice and -23.5º at the winter solstice. This is only valid for the northern hemisphere, while it is inverted for the southern hemisphere.

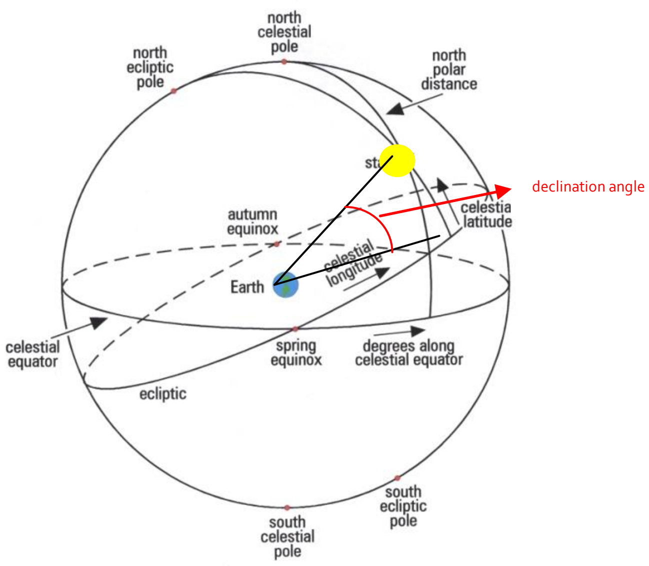


Figure 7 Celestial sphere that shows the Sun's apparent path and the declination angle (δ) [14]

In Figure 7 is represented the apparent way in which the Sun moves in the celestial sphere and the angle of solar declination.

The intersection of the Earth's equatorial plane with the apparent revolution plane of the Sun around the Earth, the ecliptic, as mentioned before, forms an angle close to 23.5º. So, the relative position of the Sun over the equatorial plane of the celestial sphere describes the solar declination. The principle cause of the solar declination's value variation is the 'leap year cycle', which during four years can cause a small variation of 10' in correspondence to the equinox and less than 1' in correspondence to the solstice.

During the day, the maximum variation of the solar declination is less than 0.5º. Then, if the solar declination is supposed to be constant during the day, the error made in the calculation of the zenith and azimuth angle is at least 0.5º.

There are several expressions available to calculate the solar declination, but the more used and the one that is going to be applied is the Perrin de Brichambaut's equation:

Equation 7

Where represents the number of day of the year, that takes values between 1(1st of January) to 365 (31st of December). Also, it should be considered that February always has 28 days.

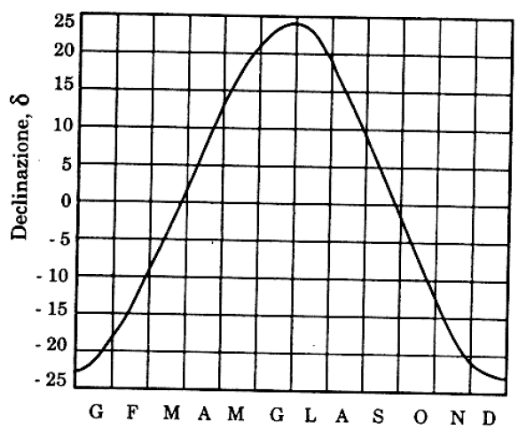


Figure 8 Diagram of solar declination's annual tendency[9]

2.3.2. Actual and conventional solar time

The solar time depends on the rotation of the Earth around its own axis, and also of the revolution path around the Sun. The solar day is a time interval that takes place because the Sun rises until the end of a cycle for a stationary observer placed on the Earth. This interval is not constant because it changes through the year due to two reasons.

The first reason is that the angular speed of the Earth around the Sun is not constant; the maximum velocity is acquired at the perihelion and the minimum at the aphelion. So, it can be deduced that maximum length of the day is achieved when the Sun goes across the meridian close to the aphelion. The difference among these periods and the mean solar day is called the solar equation due to the eccentricity (curve 1 of Figure 9).

The second reason is due to the fact that the ecliptic plane respect to the equator of the sky or rather that the position of the Earth axis is inclined respect to the ecliptic plane. This angle, as it was said before, is about 23° 27′ 8.2″. The difference between the day length and the mean solar day, for this last reason, is called time equation due to the obliquity (curve 2 of Figure 9).

These two time equation lead to define the complex time equation E_T (curve 3 of Figure 9).

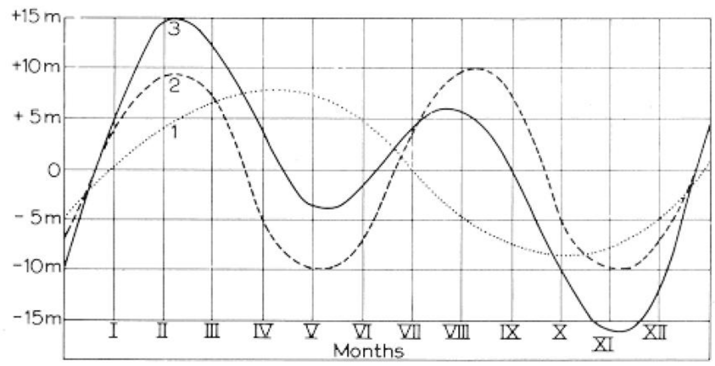


Figure 9 Time equation, E_T

Nevertheless, in general, the solar time can be obtained knowing the conventional hour and the longitude of the observation point:

Equation 8

Where is the clock time, is the longitude of the reference meridian, is the longitude of the observing point. represents a correction, that varies throughout the year, called exactly time equation. The value of can be obtained from Figure 9 or from the following relation:

Equation 9

2.3.3. Earth-Sun relative position

In order to be able to calculate the solar radiation arriving to a plane in the terrestrial surface the Sun relative position at the sky and the position of the plane should be known. The Sun position is defined if the reference system is specified.

It is supposed that the observer is placed in the Earth and the celestial sphere, logically concentric to the Earth.

The observer presents, at any time, a position in the sky identified by its *zenith*, which is the corresponding point of the intersection between the sky and the normal of the terrestrial surface, where the observer is placed.

The *zenith angle* is the angle formed by the zenith direction with the union of the Sun with the observer. It can take values between ° and °.

The position of the Sun respect to one point on the Earth and determined by the solar altitude angle, α, and by the azimuthal angle, .

The *solar altitude angle* ( ) is the angle formed from the direction of the solar rays with the horizontal plane.

The *azimuthal angle* ( ) is the angle formed between the solar rays projection over the horizontal plane and the southern direction. It takes a positive value if the projection is to the East (before midday) and it is negative if it goes towards the West (after midday). Besides, it can vary between ° and °.

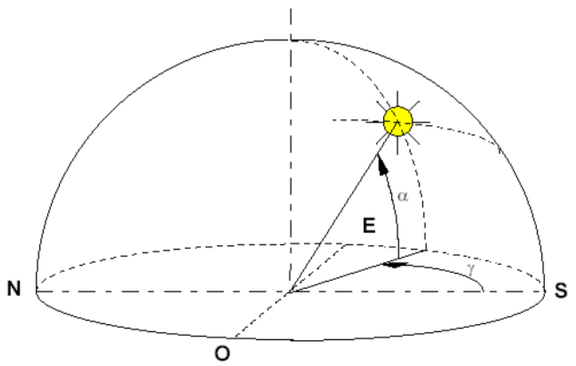


Figure 10 Solar altitude angle (α) and azimuthal angle (γ)

These two angles depend of the declination (δ) , the latitude ( ) and the hourly angle ( ).

The *hourly angle* ( ) is defined as the angular distance between the Sun and its position at noon along its apparent trajectory across the sky; and also equal to the angle to which the Earth must rotate through in order to move over the local meridian. This angle is null at midday, positive in the morning and negative in the afternoon. So, the next expression results:

Equation 10

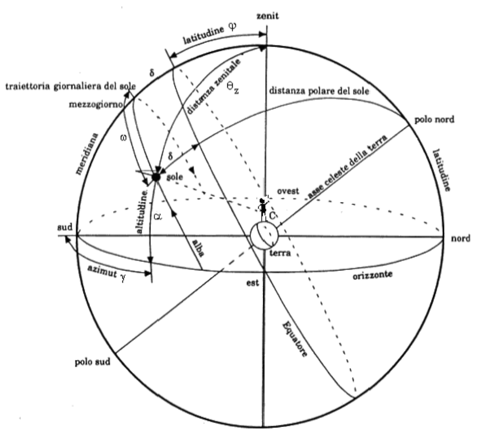


Figure 11 Celestial sphere and the Sun coordinates relative to an observer placed at point C. [9]

Once these angles are defined, it can be said that for a certain location, a geographical position, in absence of atmospheric refraction (for practical purposes can be ignored, because this hypothesis leads to a light subestimation of the real solar height of more than 34′ at the horizon), the Sun's position at every moment of the year can be obtained by the following trigonometric relation:

Equation 11

Equation 12

Where is the latitude of the location.

In the case in which is wished the relative position between the Sun and an inclined plane, it is needed to know the tilting angle of the plane respect to the horizontal (β), and the *azimuthal angle* or *azimuth* ( ) of the plane. This is the angle formed between the projection of the normal to the plane surface with the southern direction at the northern hemisphere.

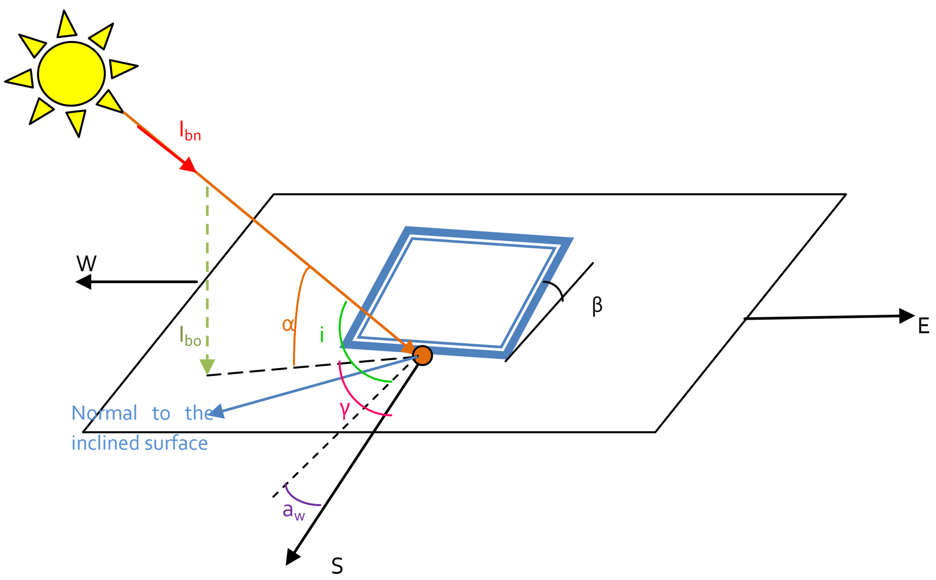


Figure 12 Relative position of the Sun to an inclined plan

2.3.4. Solar path

It is possible to represent graphically the Sun's apparent motion through the sky by means of the *solar path diagram*, or *the polar diagram* (projection over the horizontal plane) or the *cylindrical diagram* (projection over the vertical).

In those diagrams, once the latitude is determined, they provide the solar height (α), the azimuthal angle (γ), in different periods of the year. These values depend of the time of the day, the day of the year and the placement. Anyhow, they can be computed making use of the expressions previously showed.

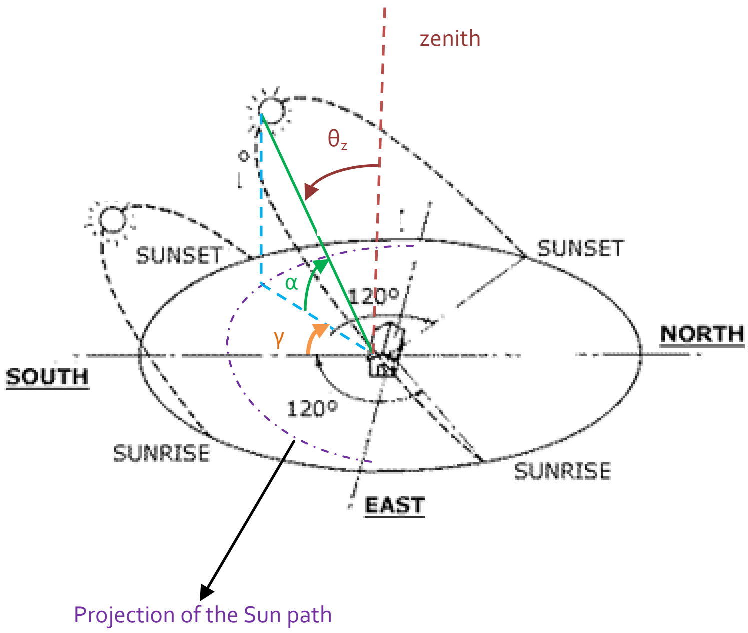


Figure 13 Sun path construction

The **solar polar diagram** is the projection of the Sun path on the horizontal plane, graphically obtained by plotting the values of the solar height and the azimuth, calculated by using the Equation 11 and Equation 12 of the considered location, as function of the actual solar time and the declination.

It is possible to represent the apparent movement of the Sun along the sky for every hour of the day and for every month of the year, fixing a system of angle measure, the sun height and the solar azimuth. With a spreadsheet and varying a parameter (the latitude) it is possible to build the solar path related to the chosen location.

In Figure 14 it is shown an example of the resulting diagram. As it can be appreciated the solar path is longer in summer months and shorter during winter months.

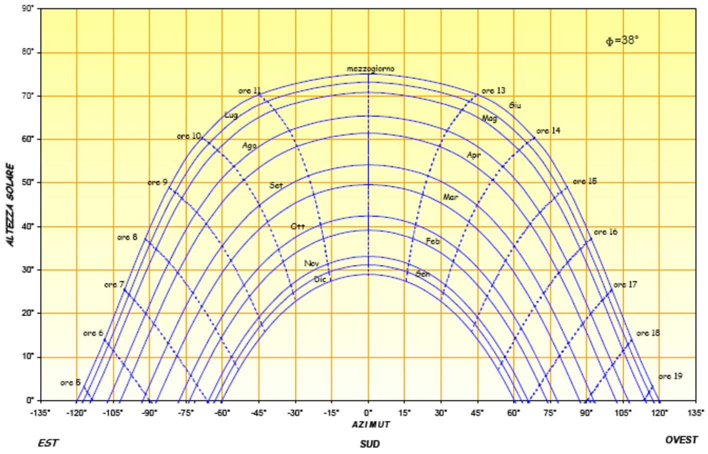


Figure 14 Solar diagram for N

2.4. Photovoltaic solar energy

Among the different applications of the solar energy it can be highlight the following ones:

- Passive solar energy

It consists of the direct collection of the solar radiation from structural elements of a building, bioclimatic architecture. This kind of energy will allow having a considerable energy saving. At the same time, the bioclimatic architecture has different objectives.

  - Limit the energetic losses of the building, facing and designing properly the shape of the building, organizing the interiors and using protecting surroundings.
  - Optimize the solar contributions, by means of glass surfaces and with passive system of solar reception.
  - Use constructive materials that require a small amount of energy on their transformation or their manufacturing.

- Solar thermal energy

The solar thermal energy is based on the thermal exploitation of solar radiation, its main and fundamental implementation is the domestic hot water production. The incidence of solar rays on the collector allows heating the fluid that flows inside itself. This heat is transferred to the drinking water through an exchanger and normally stays accumulated in a tank prepared for its future use.

- Solar photovoltaic energy

Through the discover of the photovoltaic effect, as it will be detailed later, has allowed the humanity converting the energy released from the sun, in the form of solar radiation, directly in electric energy.

As well as being able to generate electricity directly, the sun is the origin of all other renewable energy sources. Thus, it is the sun's heat on the earth and the water that causes the differences in pressure that produce the wind, the source of wind power. The sun is also the main driver of the water cycle, evaporating water from the oceans, which falls to the earth as rain, where it becomes a resource for hydroelectric power. The sun is also the essential driver of photosynthesis, and therefore the origin of the energy used in biomass.

2.4.1. Photovoltaic effect

The photovoltaic effect is the direct conversion, in a device called photovoltaic solar cell, of electromagnetic radiation in electric current. This effect can be produced in solids, liquids and gases. Today it is reached the best efficiencies in solids. Then the concept of photovoltaic conversion will be detailed.

The matter is constituted by atoms, which are also made up by two parts, the core, with positive electric charge and the electrons, with negative charge that compensate the core one, in this way it is achieved a neutral body. The more external electrons are known as valence electrons.

Semiconductors are used in the manufacture of the solar cells due to the energy that joins the valence electrons to the core is similar to the energy that the photons that form the sunlight own. When the sunlight hits a semiconductor (generally Silicon), its photons provide an amount of energy needed to the valence electrons in order to break their linkage and release them to run through the material. For every electron released it appears a hollow, these hollows behave as positive charged particulates. When in the semiconductor electron pairs are generated, it is said that there is a photogeneration of negative and positive charge carriers, which contribute to diminish the electric resistance of the material.

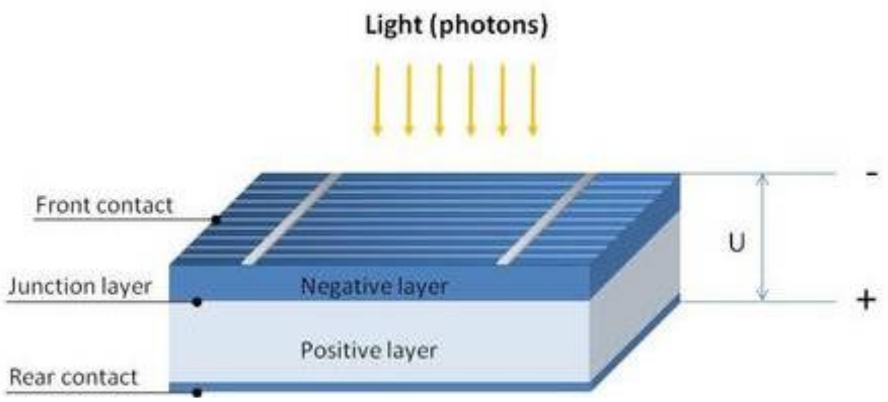


Figure 15 Sample of a photovoltaic cell [15]

Traditional solar cells are made from silicon, are usually flat-plate, and generally are the most efficient. Second-generation solar cells are called thin-film solar cells because they are made from amorphous silicon or nonsilicon materials such as cadmium telluride. Thin film solar cells use layers of semiconductor materials only a few micrometers thick. Because of their flexibility, thin film solar cells can double as rooftop shingles and tiles, building facades, or gazing for skylights. Third-generation solar cells are being made from variety of new materials besides silicon, including solar inks using conventional printing press technologies, solar dyes, and conductive plastics. Some new solar cells use plastic lenses or mirrors to concentrate sunlight onto a small piece of high efficiency PV material. The PV material is more expensive, but because so little is needed, these systems are becoming cost effective for use by utilities and industry.

The physical performance of a solar cell is measured in terms of its conversion efficiency. Currently, commercially available solar cells achieve efficiencies of approximately 15%. Economically, the price of solar electricity as cost per kilowatt-hour is the most important benchmark. It is expected, that the costs of photovoltaic energy will further decrease and reach grid-parity (competitiveness with peak power prices) between 2015 and 2020 (depending upon location and irradiation).

2.4.2. PV solar cells

The PV cell is formed by the union of two semiconductor materials. Type n, with electrons in higher energy levels somewhat linked to chemical bonds among atoms; and other type p, with gaps or electron absence in these levels. From the joint of these two type p and n semiconductors, results the new p-n union type, with electrical connections both in the upper and lower part. The thickness of this joint can vary, from less than one micron (which is the case of amorphous silicon), to hundreds of microns (in the case of crystalline silicon).

The p-n union allows the appearance of an electric field in the cell (from n to p side) that separates the pairs: gaps, positive charges, are run to p side what makes the extraction of an electron from the metal that constitutes the contact. Electrons, negative charges, are run to n side contact injecting them in the metal. This makes possible the maintenance of an electric current throughout the external loop and, therefore, the performance of the cell as a photovoltaic generator. In the following figure, the behaviour is simply shown:

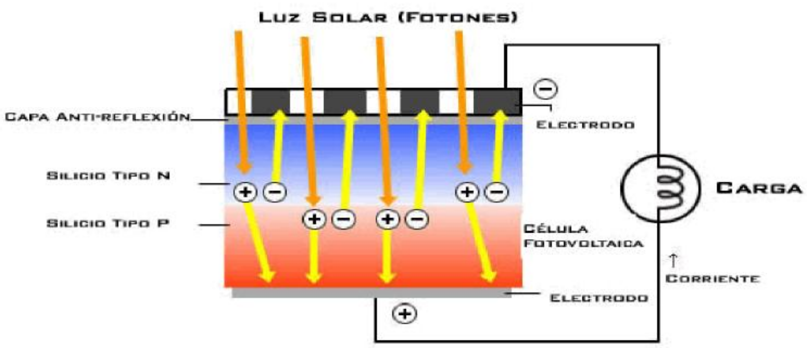


Figure 16 Solar cell performance [16]

The voltage depends on the physic-chemical properties of the building materials. The temperature rise produces a negative effect, the decrease in the temperature work. The operating voltage of the cell is around 0.5 V. The intensity of the generated current is proportional to the surface exposed to the sun and to the intensity of the incoming radiation.

There are four main categories of photovoltaic cells: c-Si (crystalline silicon) solar cells, thin film solar cells, multi -junction solar cells and new technologies (including organic solar cells).

C-Si (crystalline silicon)

The two types of crystalline cells are briefly described:

- *Monocrystalline silicon*: the cells are only made by a single silicon crystal of high purity. The efficiency of these modules has reached 17%, and the manufacturers assure a lifetime of 25 years due to its reliability. Atoms are perfectly ordered. At the crystallization process the atoms are deposited on the crystal always respecting the same order. They show a monochromatic colour: bluish, dark and with a certain metal bright.
- *Polycrystalline silicon*: this technology was developed in order to lower the manufacturing costs. It is formed by the association of silicon crystals where the atoms' alignment directions change time to time during the deposition process. These cells present a lower efficiency than monocrystalline silicon ones but it has been checked that 15% efficiencies can be reached with guaranties of 20 years of lifetime, depending on the manufacturer. Their appearance is like an amalgam of crystals with bluish tones and metal greys.

Thin film solar cells

A thin-film solar cell (TFSC) is a solar cell that is made by depositing one or more thin layers (thin film) of photovoltaic material on a substrate. The thickness range of such a layer is wide and varies from a few nanometers to tens of micrometers.

Many different photovoltaic materials are deposited with various deposition methods on a variety of substrates. Thin-film solar cells are usually categorized according to the photovoltaic material used:

- *Amorphous silicon*: This kind of cell has a geometrical structure lack, the crystalline structure has disappeared and the silicon has been deposited forming a thin layer on a transparent support. Nowadays, its efficiency has risen around a range from 5 to 10%. Product warranty can be up to 10 years depending on manufacturer. Its look is dark brown-grey. Both the market price and the qualities of mono and polycrystalline silicones are similar, whereas amorphous silicon is the most economical; however it degenerates before with the time.
- *Cadmium Telluride (CdTe)*
- *Copper indium gallium selenide (CIS or CIGS)*

Multi -junction solar cells

The fundamental difference between multi-junction solar cells and c-Si solar cells is the number of p-n junctions connected in series. In order to better cover the solar spectrum, suitable materials must be chosen for each p-n junction.

Dual junction cells can be made on *Gallium arsenide GaAr* wafers.

Triple junction cells consisting of Indium gallium phosphate *InGaP*, Gallium arsenide *GaAr* or Indium gallium arsenide *InGaAr* and Germanium *Ge* can be fabricated on germanium wafers.

These technologies are mainly used in optical concentrator systems.

MJ solar cells are preferred, because of the high cost, in space. Terrestrial applications are still being tested.

In the figure below, the different technologies are compared.

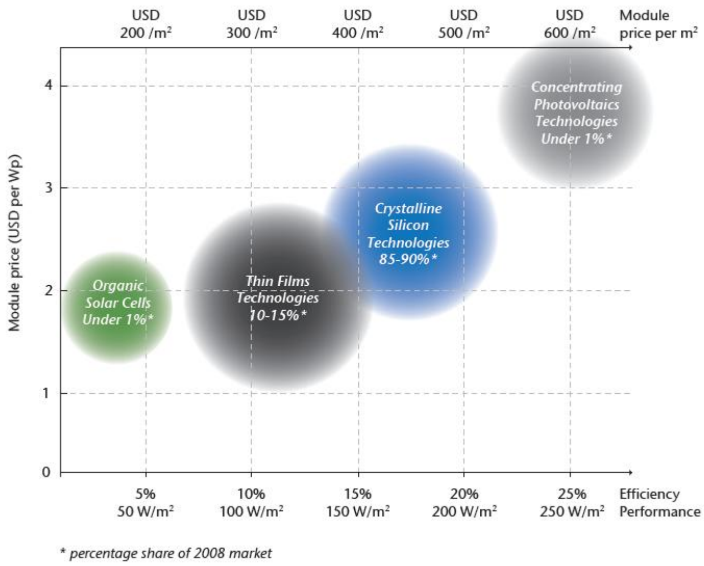


Figure 17 Current performance and price of different PV technologies [12]

2.4.3. Photovoltaic technologies

In first place an installation classification as a function of the installed power will be established, and then a second classification will be done according to the subsequent implementation.

The power of the solar PV installations is given in Wp (peak Watts), this power corresponds to the one given by the solar modules at 25ºC at irradiation conditions of 1000W/m^2. The power in Wp, is the maximum power that in theory the PV module can provide. There are [18] three ranges of power for PV installations that are detailed below:

- Small-sized installations of 3 kWp, up to 5 kWp. Generally, these are isolated rural applications because of being a clean solution and, sometimes, economic. They can be also connected to the grid on the roof of private houses. The power generated with this type of installations almost all the energetic consumption can be met at average housing with 2 or 3 people.
- Medium-sized installations of 30 kWp, with a range between 5 and 100 kWp. They are typically generators in rural centralized electrifications, or on the contrary, connected to a set of buildings. The 30 kWp installation in a building could meet the energetic demand of 10 average housing.
- Big-sized installation of 300 kWp, with ranges between 100 kWp and 1MWp. These ones use to be connected to the grid, in a wide area, generally enterprises, interested in the environment and at the same time, strengthen their image. A 300 kWp installation can satisfy the demand of an average building.
- 3 MWp photovoltaic plants with ranges between 1 and 50 MWp. They are generation plants, promoted by business partnership, in which one of the enterprises is the distributor obtaining, in this way, an environmental friendly electric generation and, at the same time, economic compensation. With this level of generation energetic demands in small cores of population can be satisfied.

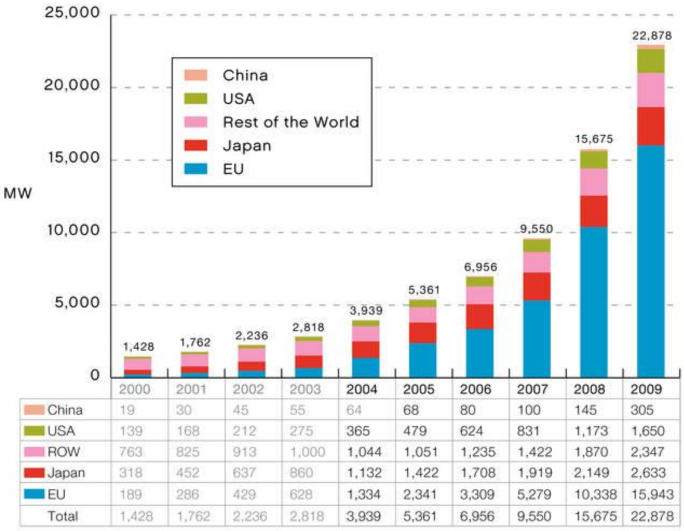
Finally we will proceed with the second classification as a function of the electric grid connection:

In the first place, the isolated from the grid installations are found, whose objective is satisfy the electric energy demand from a certain location where the electric grid does not arrive. In second place the facilities connected to the grid are placed, they are generating installation of electric energy, whose purpose is the injection of this energy to the grid.

- Off-grid installations. This category emerged to cover the electric energy demand from isolated places that do not have conventional electric grid due to the difficulties to establish it for topographical reasons. This kind of installation, nowadays, is only used in developing countries. There is also other industrial field in which it can be applied, for remote applications are very frequent in the telecommunications field, especially to link remote rural areas to the rest of the country. These applications are cost competitive today as they enable to bring power in areas far away from electric mains, avoiding the high cost of installing cabled networks.
- Grid-connected installations. This type of facilities has as main feature, that all the produced energy is injected to the distribution network of the power company. In the past years, and due to the huge legislation development and electricity tariff produced by this kind of installations, they number of them is growing. Among them it is possible to find them in houses connected to the local electricity network allows any excess power produced to feed the electricity grid and to sell it to the utility; or solar farms that produce a large quantity of photovoltaic electricity in a single point. The size of these plants range from several hundred kilowatts to several megawatts.

2.4.4. Market trends

The global PV market has experienced a huge growth for more than one decade ago with an average of annual increase rate of 40% [12] .The cumulative installed PV power capacity has grown from 0.1 GW in 1992 to 15 GW in 2008. Annual worldwide installed new capacity in 2008 grew almost 6 GW in 2008.



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
China	19	30	45	55	64	68	80	100	145	305
USA	139	168	212	275	365	479	624	831	1,173	1,650
ROW	763	825	913	1,000	1,044	1,051	1,235	1,422	1,870	2,347
Japan	318	452	637	860	1,132	1,422	1,708	1,919	2,149	2,633
EU	189	286	429	628	1,334	2,341	3,309	5,279	10,338	15,943
Total	1,428	1,762	2,236	2,818	3,939	5,361	6,956	9,550	15,675	22,878

Figure 18 Cumulative installed global PV capacity [15]

The four countries with the higher cumulative installed PV capacity have one GW or above and they are Germany (5.3 GW), Spain (3.4GW), Japan (2.1 GW) and the US (1.2 GW). These countries account for almost 80 % of the total global capacity (Figure 19). Now, other countries (such as Australia, China, France, Greece, India, Italy, Korea or Portugal) are increasing their total PV power installed due to the new policies and economic support schemes.

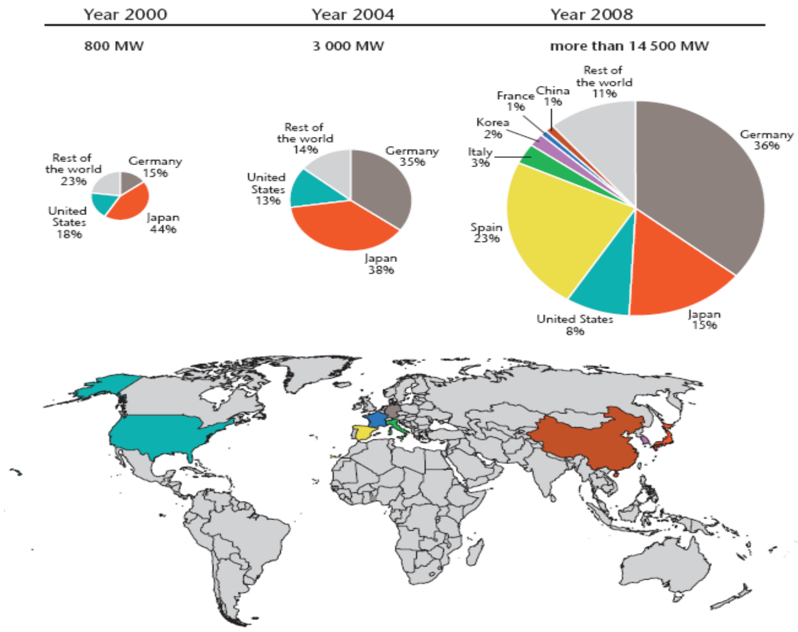


Figure 19 Solar PV markets in leading countries [12]

In an optimistic scenario, by the year 2012, a worldwide installed capacity of 44 GW could be achieved, which would be the same power generated by 44 nuclear reactors.

Worldwide public expenditures for PV research and development (R&D) have substantially increased over the past decade. R&D efforts are important all along the value chain of energy generation; from raw material production to the manufacturing of modules and balance-of-system components. Solar cell and module research constitutes the largest fraction of the R&D portion, typically 75 % of total expenditures (*IEA PVPS 2009*).

A number of major government and industry R&D efforts aim to make PV a mainstream power source within the next decade including the European Union's SET Plan, the European PV Technology Platform's, the Solar America Initiative (SAI), Japan's PV roadmap towards 2030 (PV2030), etc.

An accelerated outlook is justified by the recent PV market growth and associated cost reductions – the global PV market more than doubled reductions in one year from 2001 to 2008 and system prices fell 40% between 2008 and 2009 [12] This acceleration in the deployment of PV has been unleashed by the adoption of PV incentives schemes in an increasing number of countries. The development of the technology is expected to increase more in countries having a solar irradiation level and high retail electricity costs. This roadmap also assumes the continuation of an evolving, favourable and balanced policy framework for market deployment and technology development in many countries on the longer term.

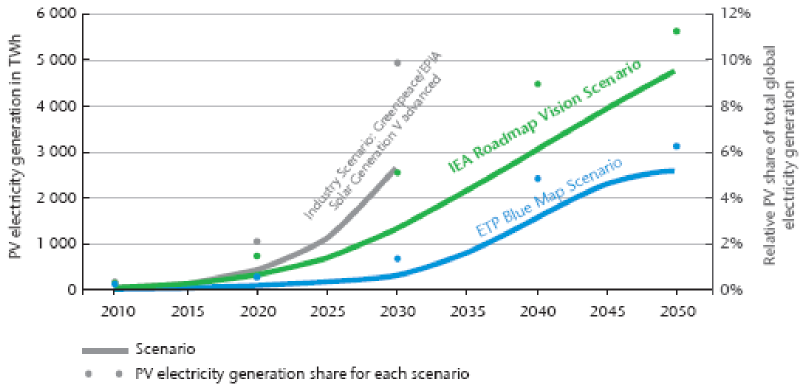


Figure 20 Global PV power generation relative share of total electricity generation [17]

The roadmap assumes an average annual market growth rate of 17 % in the next decade, leading to a global cumulative installed PV power capacity of 200 GW by 2020. This level of PV market growth is justified by the achievement of grid parity predicted to occur in an increasing number of countries. This parity will be more easily achieved by policy incentives that support the deployment and decrease overall costs.

2.5. Photovoltaic energy in Italy

The "Conto Energia" promoting Programme is eventually ensuring a stable situation, providing the basis for the expansion of PV market in Italy. Bureaucratic problems related to the incentive mechanism have been overcome while the ones concerning plant construction and grid connection seem to have been smoothed out. In this context, during the last year photovoltaic is becoming more and more important and the PV market seems to be followed by an adequate growth of the national PV industry.

A preliminary evaluation of PV power installed in Italy during 2009 sums up to about 500 MWp. Then the total installed and operating power in Italy at the end of 2009 should result in about 900-960 MWp with a growth rate of around 50%, in respect to the previous year. At this growth rate, the overall cumulative power which is supported by the "Conto energia" Programme (1200 MW), is expected to be reached by mid 2011.[12]

2.5.1. National program

A new programme "Conto energia 2011-2013" has been developed. The beneficiaries of the incentive tariff are the facilities that are accepted as new construction. There are four categories:

- Solar photovoltaic installations
- Photovoltaic installations with innovative features
- Concentration installations
- Photovoltaic installations with technological innovation

For each category there is foreseen a maximum power to be incentivized. In the concentration case, which is the one we are interested on, the power limit is 200 MW and the maximum duration for them is at most 20 years.

This is an innovation compared to the last program is the introduction of these kind of installations that were not included before for the reception of incentives. This is the main new feature of this regulation.

2.5.2. Comparison with the Spanish

In Spain a new regulatory framework was developed in 2009 with the purpose of rationalize the deployment of PV in Spain, in order to control the impact of the feed in tariff in the national economic situation. The new regulatory framework implies a 30% reduction of the feed-in-tariff and further progressive cuts, which could reach 10% annually. A quota of 500 MW in 2009 and similar to the next three years has been established, together with the creating of a register for allocating new capacity. As a result of the new situation, in 2009, 2488 installations were authorised, with a total capacity of 502 MW. This is in contrast to the capacity installed in the previous year; 2755MW, according to the National Energy Commission's data.

This new regulatory conditions, combined with the global financial crisis, have dramatically altered the sector's industrial fabric, with 20 000 jobs lost since the reforms; according to ASIF, the national PV industry association.

The regulatory framework that has defined a quota of 500 MW for the years 2009, 2010 and 2011; established that the tariffs will be decreasing in case that the call made every three months is completed. There is a tendency to increase the installations of PV in buildings and decrease them on ground. The evolution of the tariffs expected, depending on the percentage of reductions up to 2020, is shown in the following figure.

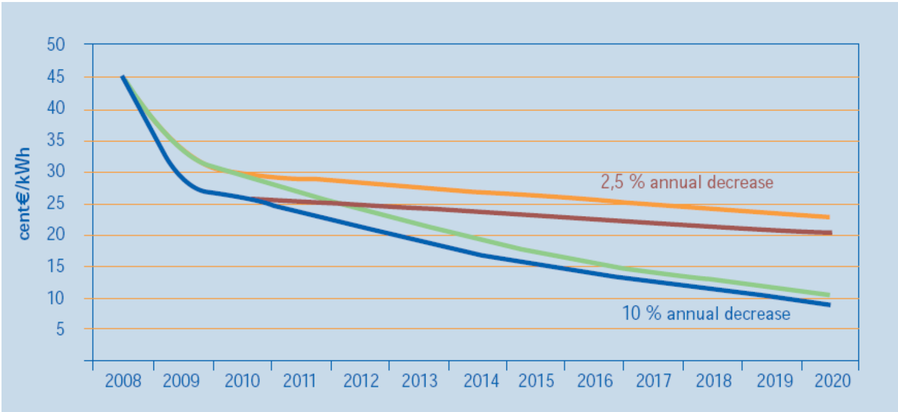


Figure 21 Evolution of the rate for photovoltaic installations according to the Royal Decree application.

Nevertheless, in this moment there is a discussion on how the target for 2020 is going to be defined, and also, what will be the regulatory framework and the tariff system for that period after 2011.

No changes in the main lines for R&D have occurred since the lasts years, with quite relevant activity from public and private centres. The main lines of R&D cover the improvement of efficiency on the crystalline silicon technologies, including automation of processes, solar grade silicon processes, thin film materials and cells, integration of PV in the building sector, concentration PV ad new materials, such as organic cells.

The vast bulk of Spain's installed PV capacity in is multi-megawatt ground-based arrays, often rated in tens of megawatts. 37% of the facilities in the ground have tracking systems, of which 24% are two axis tracking and 13% single axis tracking. The new regulatory framework has established a better price for roof and facades installations, and it is expected that these types of PV installations will take a bigger share of the market in the future. In 2009, almost 50% of the new, authorised installations were integrated in the built environment, with a further increase in the share in the coming years.

The drastic change in market deployment in 2009 has produced a relevant impact on PV industry, with an important job reduction due to the new targets established, as well as the impasse created with the new situation, which produced a market paralysis for almost six months. Nevertheless, once the new framework was established with a market of 500 MW, the situation is expected to recover slowly.

Despite of drastic reduction suffered in the market in 2009, compared to the previous year, the new stable framework and the discussions that are taking place, to the definition of the new national Renewable Energy Plan that is defined to comply with the compromise of reaching 20% of primary energy from renewables, Spain still envisions a good frame for the deployment of PV.

The continuous cost reduction in PV sector opens the opportunity to reach grid parity in a few years, and this will imply a new situation, that for sure will increase drastically the penetration of PV in the portfolio of energy solutions.

2.6. Photovoltaic concentrators

Different studies, [7] [8] , indicate that the cost of the energy produced by photovoltaic concentrators is strongly reduced respect to planar panels, above all in countries in which there is a large sun radiation most of the year. The reduction of the cost comes from the reduction of the catchment photovoltaic surface of high efficiency and therefore, expensive, through the employment of an optical system that concentrates the sun radiation.

The concept is simple, since silicon is the most expensive part of the system and the PV cell can theoretically produce more energy if it is exposed to higher light fluxes; a system to concentrate a lot of solar light on a reduced amount of high-efficiency PV cells can be developed.

Some examples of concentrator systems have being tested resulting a variety of solutions but none of them has demonstrate its real functionality. The economic suitability has been, for a long time, a problem because of the low availability of photovoltaic cells for operating in concentrating conditions. Nowadays, all this technologies have reached, for different reasons, a level of maturity enough to develop a reliable and economically convenient system.

The key point to understand the potential economic benefits of this technology is that the most part of the materials and resources used in the construction of a concentrating system are made of reflective surfaces; apart from the control and the tracking system, which they are already mature enough. The amount of PV cells used, where the market has an inflexible offer, is highly limited. This kind of framework can go ahead to the economies of scale more than flat panels systems linked to a high intrinsic cost material.

Analyzing in detail the components of a concentration photovoltaic system, the most important part, apparently and probably, is the big surface of mirrors, the primary concentrator. Its main objective is to concentrate the light coming from the sun on a photovoltaic receiver placed at the optical focus of the system. If the system is consists of a set of flat mirrors, in order to have uniform illuminated focal area, the most luminous point is reached by a parabolic receiver. The ideal design would be built by a single parabolic mirror, but, trying to reduce the costs, this choice is not the most appropriate one. In order to increase as much as possible the reflection coefficient, dielectric coatings or composite materials can be used.

One of the most important aspects of the concentrator is that, for proper performance, the sun should be found always at the optical axis of the primary concentrator. So, for this reason, the system needs any kind of movement that allows it following the apparent sun movement. This is also an advantage for the energy produced by the system because, in contrast to stationary flat panels, the system always offers the maximum surface to the sun reaching the best of energy.

The core of the system is found at the photovoltaic receiver formed by a small panel of high efficiency photovoltaic cells designed to work under concentrating conditions. In past years, new cells for concentrator have arrived to the market with higher reliability and reasonable prices. Due to the high light concentration at the receiver a cooling system should be implemented in order to keep the working temperature of the cell under 90º C.

Figure 22 Parabolic system of concentrators placed at Ciudad Real, Spain[20]

2.6.1. Advantages of CPV technology

The value of CPV compared to PV can be summarized as [22] :

- Lower capital investment because of the reduced use of semiconductor material compared with flat-plate silicon reducing the risk of the investor and allowing more rapid adjustments of plans based on changing market.
- High energy yield (kWh/installed kW) associated with the use of tracking and small temperature coefficient; in areas with high direct-normal irradiance, this can be a significant effect, providing lower cost of electricity even for products with higher €/W cost.
- Higher efficiency allowing smaller, module area; in some cases, CPV requires less than half the module area to deliver the same power.
- Lower product costs expected because of a reduced use of semiconductor material compared with flat-plate silicon and because a steeper learning curve.
- Better match to load profile because of excellent performance in late afternoon (as a result of tracking and lower temperature coefficients).

- Qualitatively different approach that complements low-efficiency approaches and contributes to a strong technology portfolio for solar, especially for the sunniest locations.

CPV joins the rest of PV in providing these benefits:

- Renewable electricity source with a cost that already competes with the conventional electricity sources in some locations.
- Modular: can be installed in sizes ranging from kilowatts to multiple megawatts.
- Production profile that is fairly predictable and it is a relatively good match to the load profile.
- Low maintenance.
- Can be installed with minimal environmental impact.
- Low carbon intensity and energy payback that can be less than a year

2.6.2. Behaviour of PV silicon cells under concentrated light

Single-crystal silicon photovoltaic convertors are presently used in all practical solar photovoltaic power sources. It is the cost of these convertors which primarily determines the cost of the array. To become economically feasible, the convertor cost must be reduced and low-cost techniques must be developed to efficiently integrate these devices into completed modules ready for field installation. Single-crystal silicon is not the only material from which solar arrays can be fabricated and potentially better results may be obtained from films of polycrystalline or amorphous silicon.

The main problems associated to silicon concentrated are the following ones [23] :

- The cell must be designed to have very low series resistance because of the increased current flow.
- For example, a 10% efficient solar cell generating 2W at 56x geometric concentration receives about 20 W of direct energy, of which 18 W are dissipated as heat. Therefore, solar cells at high concentration ratios have to be provided with a large area, contoured cooler or with forced convection cooling.
- Concentration systems of high concentration ratio must track the sun. This adds to the cost and involves maintenance problems. Tracking systems also have the disadvantage of being ineffective in periods of diffuse daylight, whereas nonconcentrator flat-plate systems still deliver power.

Concentrator systems offer possibilities of cost effectiveness, although they involve moving parts and cooling systems, and are unable to use diffuse sunlight. The conclusions from the research carried out by College of Engineering, King Saud University, Riyadh, Saudi Arabia, are summarized as follows [23] :

- As the incident solar intensity increases, the magnitude of the efficiency reduction, due to a constant increase in cell temperature, decreases.
- For relatively high levels of incident solar intensity, the rate of efficiency change with respect to the cell temperature depends on cell temperature.

- For a certain cell temperature range and a certain high level of incident solar intensity, the magnitude of the efficiency reduction, due to the increase of cell temperature, may reach a minimum value; and the efficiency maybe considered constant over the specified range of cell temperatures for the corresponding level of incident solar intensity.
- The free-convection cooling system of the module is efficient enough to control the cell temperature.
- The module efficiency decreases with increasing cell temperature for constant incident solar power intensity.
- The module efficiency, at a constant cell temperature, increases with increasing incident solar radiation intensity, up to a maximum value at a certain optimum incident solar intensity, the module efficiency decreases.
- As a general conclusion, the cell temperature must be kept as low as possible by means of a forced/free-convection cooling system and the concentration ratio must be adjusted to that cell temperature to get maximum efficiency.

Chapter 3

3. THE PLANAR CONCENTRATOR PROTOTYPE

Different studies [21] indicate that the energy cost from the energy produced by photovoltaic concentrators is strongly reduced respect to flat panels, especially in those countries that have a high solar irradiation most part of the year. The cost drop comes from the reduction of the high-efficiency photovoltaic surface receiver and therefore expensive, through the use of optical concentrating systems of the solar radiation.

In this field of research, an experimental innovative of medium-concentration system has been developed, for the production of energy of high efficiency from the solar source.

In this chapter the main features of the prototype are described in order to understand properly how the device geometrically works and then where the problems of efficiency come from.

3.1. Description of the installation

At the experimental appliance developed, the incident radiation is concentrated on a photovoltaic surface by means of a set of flat mirrors, or minimum curvature. These mirrors, appropriately oriented respect to the receiver panel, simulate the surface of a parabolic concentrator (See Figure 23).This solution allows a double simplification both in the manufacture phase and during the operation of the facility. This is because the mirrors present only one rotational axis with consequent simplifications of the system motions.

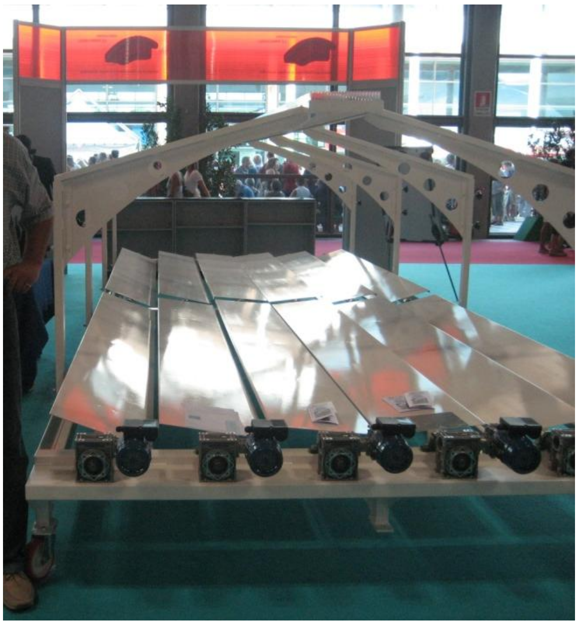


Figure 23 Experimental innovative medium-concentration PV system.

An electronic system for tracking management rotates the mirrors around a rotational axis, in such a way that the solar rays come always concentrated on the receiver panel during the sun's daily movement.

The receiver panel is made of common photovoltaic cells of polycrystalline silicon that constitutes a mature technology. Polycrystalline silicon cells endure levels of concentration of about 5-10X, enabling a remarkable reduction of the required collector surface, but keeping the advantages of a consolidated technology.

In order to remove the heat due to the solar flux a finned profile was installed at the photovoltaic cell.

This technology presents some advantages respect to the traditional flat photovoltaic panels and to the high concentration systems.

Respect to the flat panels, medium-concentration allows both more produced energy and less number of photovoltaic receivers. Besides, the efficiency of the photovoltaic cell rises with the increase in irradiation whenever they are cooled.

Regarding the high-concentration systems, medium-concentration allows the use of traditional PV cells in spite of multi junction PV cells, particularly complex and therefore, expensive. But, the use of common cells has the drawback of the release of heat due to the higher hitting flux. And, it is well known, the fact that the efficiency of the cells decreases with the temperature increase.

Different theoretic-experimental studies were developed in order to evaluate the best solution for the heat dissipation. Two possibilities were considered, forced convention with water as heat transfer fluid and natural convection with a finned surface. In the end, as it was mentioned before, the optimal cooling system for the prototype was the natural convection [21] .

3.2. Operation and components

A middle concentration system is proposed, directed to towards a strong reduction of €/W cost and based on traditional cell technology and simple tracking systems.

The system has only one tracking axis and it has been subject of study and optimization both from geometric-kinematic point of view and from electric-thermal one.

The system is divided into two subsystems:

- Tracking and reflection subsystem
- Picking and loss of heat subsystem

3.2.1. Tracking and reflection subsystem

The system is up of a series of rotating mirrors and a photovoltaic panel. The axes of the mirrors are parallel to each other and lie in a plane parallel to the panel. The optimization of the geometric configuration was performed by means of software developed under Matlab environment but this is not the scope of this work.

That software simulates the movement of the sun along the year and estimates the amount of energy hitting the panel as a function of the configuration parameters: the dimensions of mirrors and panel, the orientation of the panel, the number of mirrors, the distance between mirrors and the height of the PV panel above the mirrors.

As the place of interest was considered the city of Perugia (lat. 43º6' long. 12º23'), in Italy; in order to study the energetic effect of the sun, the incident rays can be considered parallel among them. Moreover, each mirror was divided into m*n rectangular blocks, and the centre of each block was considered as the source of the reflecting ray carrying the energy for the whole block. For simplicity sake reflection from the ground was ignored.

So, thanks to the software developed the movement of the mirrors were established for the whole year. Each one of the mirrors has its own configuration in order to follow the sun motion and focus the income radiation on the PV cell. For this reason, each mirror is rotated by its own electric motor which is controlled by a programmable logic controller (PLC) which has all the parameters.

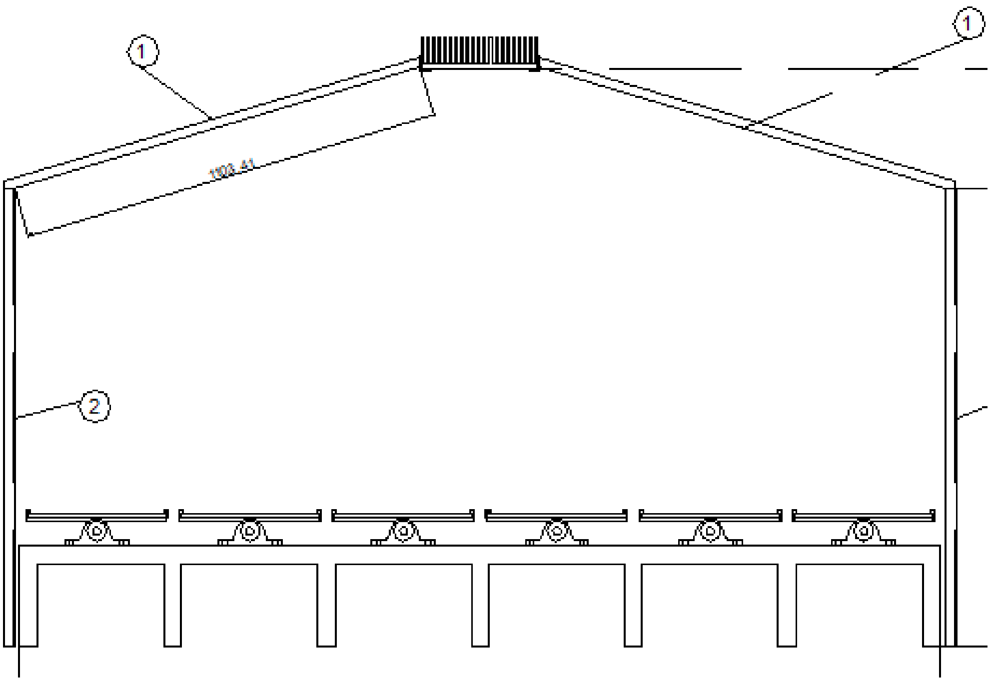


Figure 24 Frontal view of the prototype concentrator

In Figure 24 the front view of the installation is shown. It can be seen the tracking system for the mirrors which are laid on a metallic structure, parallel to the PV cell, placed above.

The movement of the mirrors' algorithm calculates, for each mirror, the rotational angle necessary for reflected rays to hit the photovoltaic receiver. The movement of the mirrors is done around a single rotational axis at the longitudinal axis direction of the mirror (north-south direction).

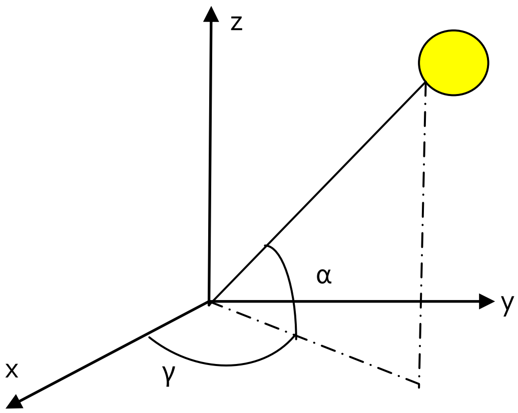


Figure 25 Solar height (α) and azimuth (γ) calculation

The algorithm, therefore, calculates the x rotation of each mirror considering the reflection at XY plane.

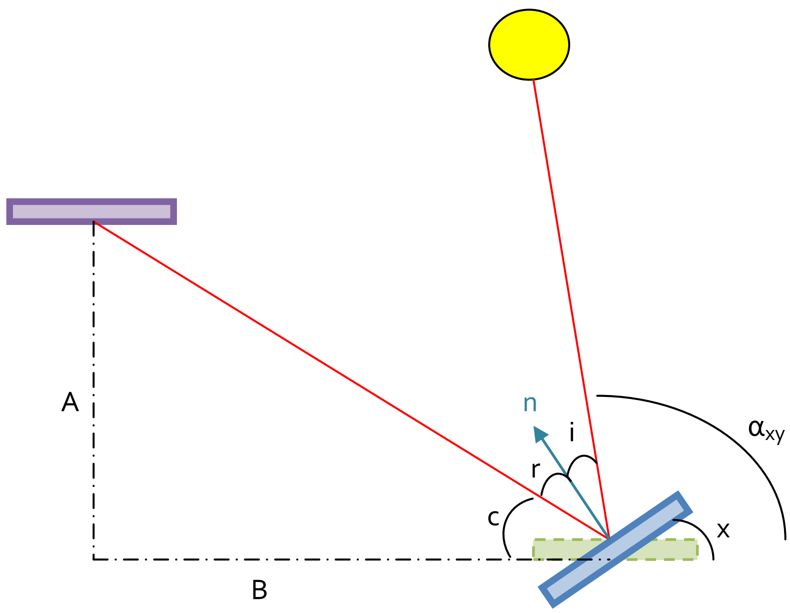


Figure 26 Rotation of mirror and angles of the configuration

The rotation of each mirror, 'x', is given by the following expression:

Equation 13

Equation 14

Where:

i is the incident angle of the solar ray respect to the normal of the rotated mirror

r is the reflection angle respect to the normal of the mirror

c is the angle between the panel and the mirror

Equation 15

Where A is the height of the panel and B is the distance of the mirror axis to the centre of the facility.

By the Snell law it is obtained that i=r, resulting that:

Equation 16

Substituting in the previous equation the following expression is reached:

Equation 17

The rotation of each mirror (for which c is being fixed) is, then, computed for each time step from the projection of the solar height on the YZ plane.

The algorithm has been implemented in a PLC that controls the mirrors of the 'Prototype 0' and its efficiency has already been proved.

In the following figure, a scheme of how the rays are concentrated in the cell is shown with an example of one mirror.

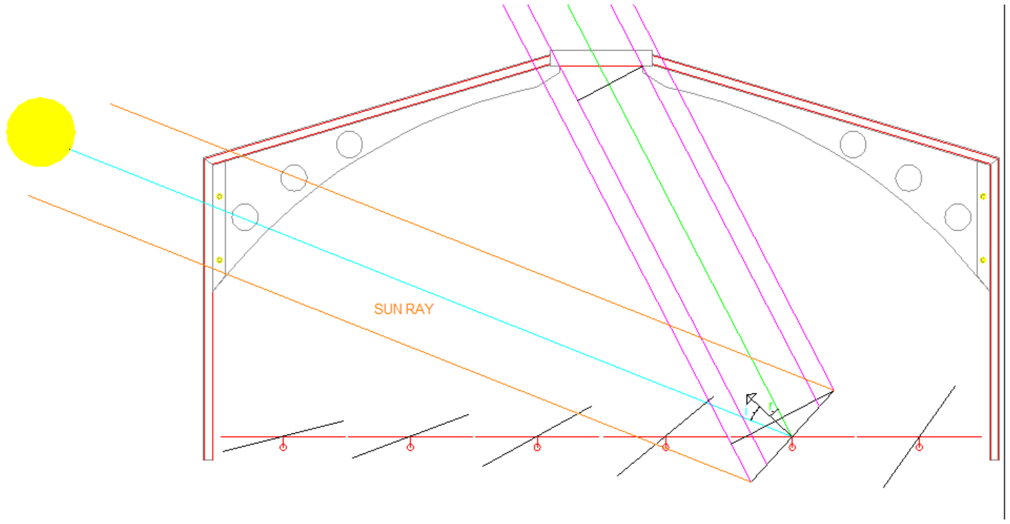


Figure 27 Scheme of the geometrical operation of the system

As it is shown in the figure, all the mirrors are rotated a certain angle depending on the day of the year and the time of the day in such a way that the incident solar ray is projected to hit the PV panel.

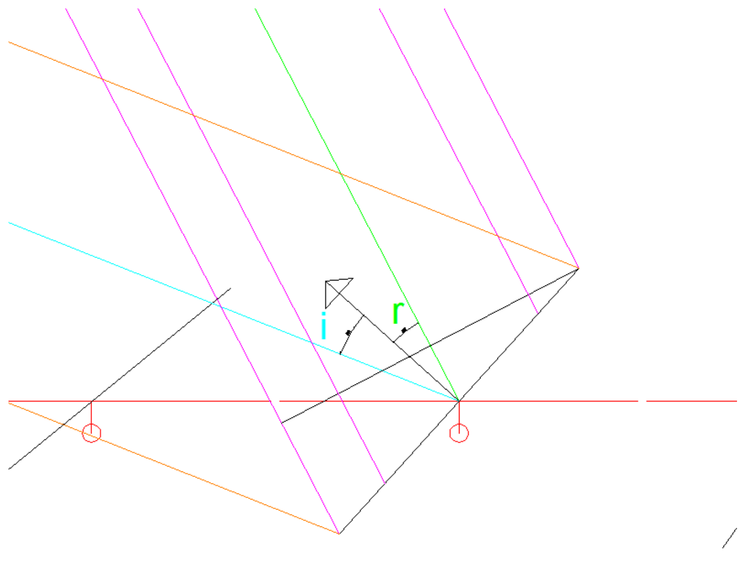


Figure 28 Detail of the mirror where the sun ray arrives

In Figure 28 a detail of the rays at the mirror is shown in order to understand better how the mirror behaves. As it is well known by optic science, the incident angle is equal to the reflected one so, the rotation of the mirror is determined easily by this principle knowing the position of the sun in the sky.

3.2.2. Picking and loss of heat subsystem

This subsystem is basically composed by the upper part of the structure, that is to say, the photovoltaic panel which is the one that picks up all the incoming radiation reflected by the mirrors, and the finned surface which is in charge of releasing the heat from the cell.

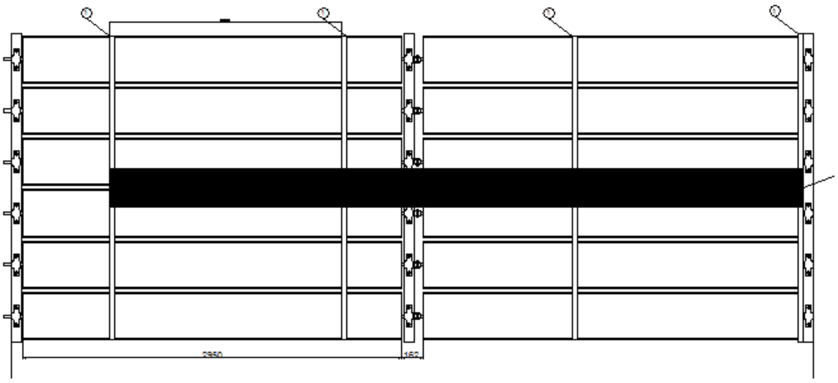


Figure 29 Top view of the prototype

At Figure 29 the horizontal position of the PV panel respect to the mirrors is shown. As it can be seen, the system is made of six mirrors but doubled, two sets of six mirrors each one, and besides, two cells, one for each set of six mirrors. But, as they are connected by an axle, only six electric engines are used.

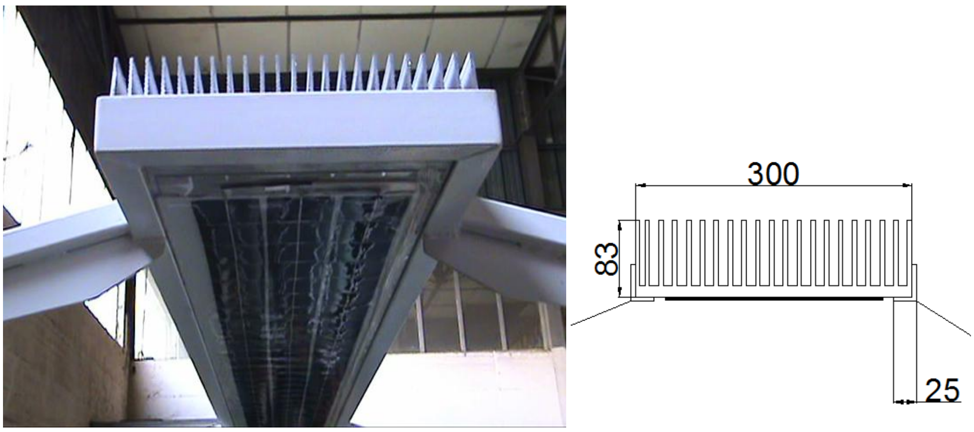


Figure 30 Detail of the PV panel and the finned surface

In Figure 30 it is shown a real image of the upper part of the installation in which it can be appreciated the finned surface place on the PV panel for cooling it. On the right hand side of it, a detail of the planes developed is shown in with the dimensions of the finned surface. As it was explained in section 2.6.2, the increase in the intensity of incoming radiation at the cell due to the concentration makes the temperature grows. This fact makes the cell efficiency decrease that is why it should be controlled by a cooling system, both free and forced convection.

Figure 31 Picture of the installation in the location where it is placed

To finish this part, picture of the 'Prototype 0' is shown. On it, the two sets of six mirrors can be seen, as well as the PV panel. Also, the six electric engines are easily found at the beginning of the axles. Finally, the electronic controller is at the right part of the picture, covered by a grey box to protect it from the atmospheric conditions.

3.2.3. 'Prototype 0' geometrical configuration

The optimal configuration for the construction of the first prototype was carried out by IPASS on Matlab environment. The simulation allowed determining that:

- The *optimum orientation* is North-South direction so that the longitudinal axes of the mirrors are placed in such direction.
- The *optimum width value* of the mirrors is 1.1 times the width of the photovoltaic panel.

Equation 18

This helps to compensate the losses due to the null inclination of the mirrors ( ) respect to the ground, because of constructive simplicity.

- The *optimum length* of each mirror is 2 times the length of the panel.

Equation 19

- The *optimum number* of mirrors is 6, compatible with the increase in electric current due to the greater incident radiation on the panel.
- The optimum value of the height of the panel respect to the mirrors is 0.5 times the total width of the mirrors.

Equation 20

After the construction of the 'Prototype 0' in a theoretical way some possible improvements for the facility were defined in order to face the reflected energy losses factors.

- Mechanical system inaccuracy.
- PLC architecture inaccuracy.
- Reflected flux dispersion due to geometrical causes.
- Reflected flux loss by the E-W axis movement absence.

Chapter 4

4. OPTIMIZATION OF THE CONFIGURATION

This chapter is the core of all this work in which, as it was explained before, a study of the geometry of the prototype is carried out. Besides, apart from its analysis, a more optimum configuration will be proposed. So, the amount of energy lost for geometrical reasons and an optimization of the configuration will be done ('Prototype 1').

In order to implement this study a previous simplification is taken, the study will only be done considering the structure in 2D, at the front view. Apart from this, some of the analyses are focused on four days of the year, the two equinoxes and the two solstices. This is because they represent the days with more, equal or less daylight of the year and this is very helpful to evaluate the efficiency changes.

4.1. Cad drawings ratio

Before starting with the numerical model in Matlab in order to obtain the total annual amount of energy the system is able to get, a geometrical analysis is done in order to obtain some values of the conversion ratio of each mirror.

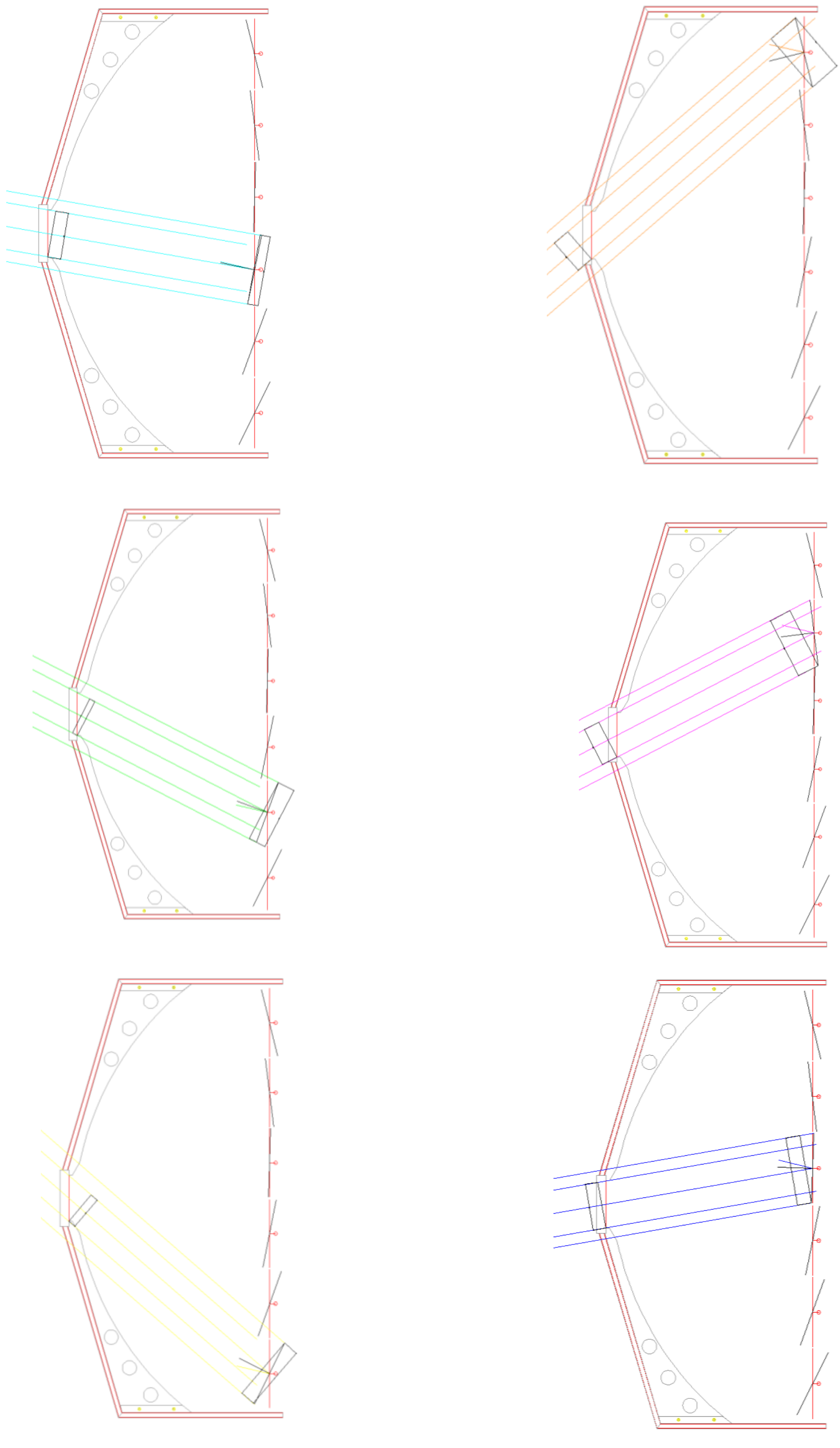
To do it, an Excel file is implemented, in which introducing the day of the year and the time of the day, all the required angles to know the physical configuration of the system are provided.

These values are given by the sun equations that have been explained in section 2.3. With the angles and by Autocad the ratios are obtained.

As it is impossible to analyse all the situations in which the system will be found, just four cases were analysed. Four days of the year were chosen, the two solstices and the two equinoxes. All of them were analysed in different situations along the day in order to try to cover the entire sun path from the sunrise to the sunset in steps of two hours. For each case, the mirrors were rotated according to the angles given by the spreadsheet and taking into account the sun inclination, so the efficient areas of the panel and the mirrors were obtained.

Since showing a huge amount of drawings in Autocad is not very illustrative, an example of one day and at one hour is only presented. In the following figure, there are six pictures, for each one of the mirrors. They were plotted separately in order not to be confused by the lines.

From the sketches, the ratio was obtained by measuring the corresponding effective areas of the PV panel and the mirror.



What really interests to the study are the results given by the drawings, not the drawings themselves. From the geometrical analysis, a set of charts with the ratios have been built for each of the discussed days.

For each time of the day shown, that is the true solar time; the ratios are calculated as the division of the efficient areas of the photovoltaic cell over the mirror — . These distances are directly measured from the Cad drawings.

4.1.1. Vernal equinox

The vernal equinox corresponds to March, the 21st and, as its meaning in Latin indicates, the night and day are approximately equally long. It occurs when the tilt of the Earth's axis is inclined neither away from nor towards the sun.

Table 1 Vernal equinox ratios for every mirror of the facility

MIRROR 1		MIRROR 2		MIRROR 3	
Time	**Ratio of areas**	**Time**	**Ratio of areas**	**Time**	**Ratio of areas**
6,61	0,554804429	6,61	0,68842992	6,61	0,84591277
8,37	0,523948399	8,37	0,6346671	8,37	0,75276688
9,87	0,511648194	9,87	0,6060386	9,87	0,69648184
11,62	0,526511751	11,62	0,60380381	11,62	0,66474285
13,25	0,584605915	13,25	0,64756256	13,25	0,6835206
15,37	0,764796134	15,37	0,79823722	15,37	0,78887604
17,12	0,99510978	17,12	0,99510978	17,12	0,91819019
17,87	1,138436947	17,87	1,08910845	17,87	0,99128507

MIRROR 4		MIRROR 5		MIRROR 6	
Time	**Ratio of areas**	**Time**	**Ratio of areas**	**Time**	**Ratio of areas**
6,61	0,99458858	6,61	1,09588011	6,61	1,05687777
8,37	0,84153272	8,37	0,87212171	8,37	0,85499463
9,87	0,74749776	9,87	0,74031992	9,87	0,69509937
11,62	0,67792398	11,62	0,63763838	11,62	0,57240229
13,25	0,66590436	13,25	0,60054061	13,25	0,52129387
15,37	0,72082997	15,37	0,61632761	15,37	0,51448882
17,12	0,79979013	17,12	0,65982123	17,12	0,53750371
17,87	0,8438019	17,87	0,68523251	17,87	0,55250153

With this data extracted from the Autocad drawings, the following graphics were plotted.

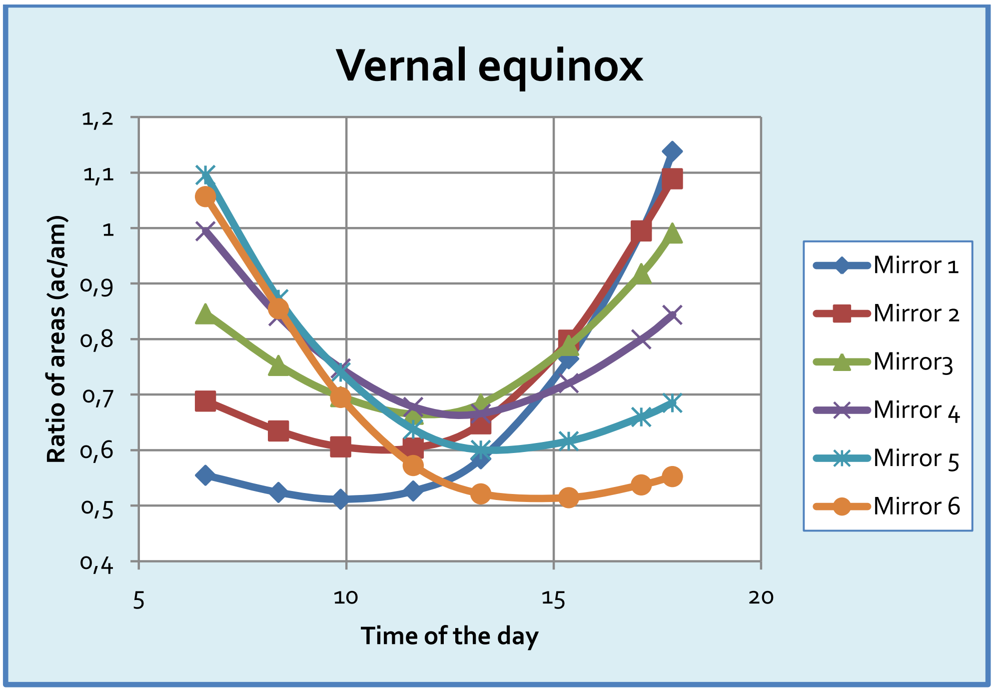


Figure 32 Vernal equinox ratio for every mirror

All mirrors have a parabolic shape, although some of them only complete a half of it but, all of them have a minimum value that is reached at midday. They have a symmetrical behaviour as symmetrical is the architecture of the installation. Mirror 1 and 6 cut each other at the same that mirrors 2 and 5 cut and mirrors 3 and 4 do too. The maximum values are reached in the early morning or in the late afternoon, taking the approximate value of 1.

Therefore, the minimum ratios are found when the higher amount of radiation takes place. This is an important conclusion for the total efficiency computation of the prototype.

4.1.2. Summer solstice

The summer solstice takes place in June, the 21st. It is the day of the year with the longest period of daylight. It occurs exactly when the Earth's axial tilt is most inclined towards the sun.

Table 2 Summer equinox ratios for every mirror of the facility

MIRROR 1		MIRROR 2		MIRROR 3	
Time	Ratio of areas	Time	Ratio of areas	Time	Ratio of areas
5,03	0,55204296	5,03	0,68398408	5,03	0,83845606
6,62	0,52809257	6,62	0,64227598	6,62	0,76628522
8,12	0,51472296	8,12	0,61536436	8,12	0,71637871
9,87	0,51263269	9,87	0,59980491	9,87	0,67977896
12,37	0,54176287	12,37	0,61399222	12,37	0,66598993
13,87	0,63251713	13,87	0,68758643	13,87	0,70999205
15,37	0,76476453	15,37	0,79820337	15,37	0,78873368
17,12	0,99525806	17,12	0,98192974	17,12	0,96041952

MIRROR 4		MIRROR 5		MIRROR 6	
Time	**Ratio of areas**	**Time**	**Ratio of areas**	**Time**	**Ratio of areas**
5,03	0,98151725	5,03	1,07627001	5,03	1,12011708
6,62	0,86351671	6,62	0,90326079	6,62	0,89392578
8,12	0,78151387	8,12	0,78778873	8,12	0,75196464
9,87	0,71320454	9,87	0,69167136	9,87	0,63748759
12,37	0,66811901	12,37	0,61865733	12,37	0,54829287
13,87	0,67649055	13,87	0,5984555	13,87	0,51197612
15,37	0,72076206	15,37	0,61625849	15,37	0,50478209
17,12	0,79991975	17,12	0,6599338	17,12	0,53761379

In order to understand better the behaviour of the mirrors, the ratios are plotted as a function of the time of the day as follows:

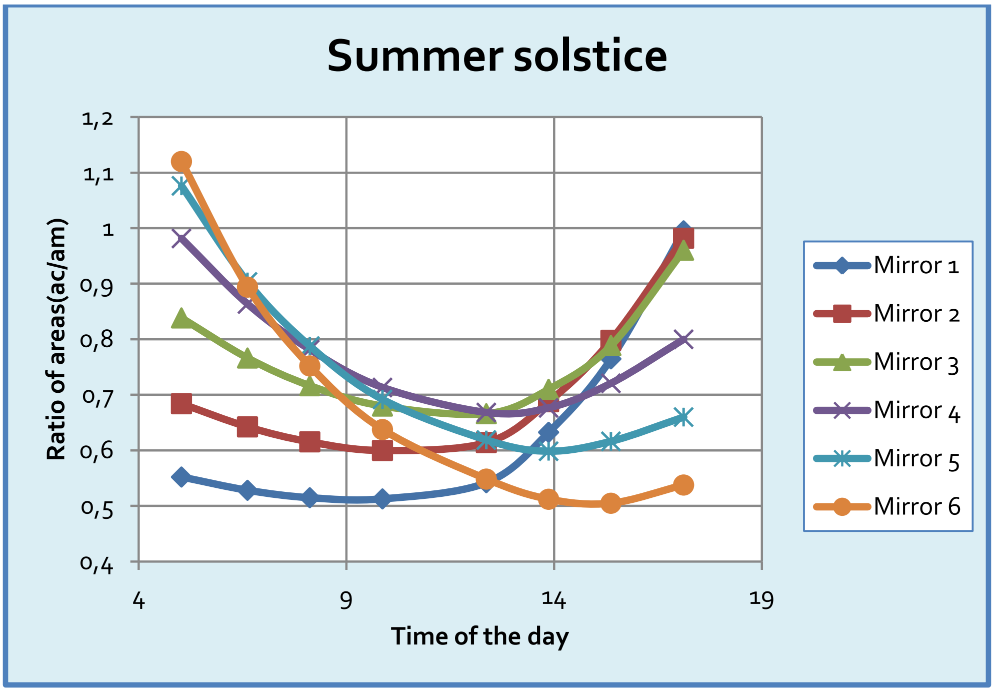


Figure 33 Summer solstice ratios for each mirror

As before, the general tendency of curves is parabolic with a symmetrical behaviour among the mirrors. The main feature to highlight is that in the values of the ratios are higher in the morning than in the afternoon for the right hand side mirrors, in contrast to what happened in the vernal equinox. The maximum value in the morning is more than 1.1 reached by the sixth mirror, compared to the Figure 32, where the maximum is reached by both. In general, the shape of the curves is more flat than in the previous case.

4.1.3. Autumnal equinox

The autumnal equinox is in September, the 21st. As it was explained before, in this day, day length is equal to night. So, by the analysis by means of Autocad the results are:

Table 3 Autumnal equinox ratios' values

MIRROR 1		MIRROR 2		MIRROR 3	
Time	Ratio of areas	Time	Ratio of areas	Time	Ratio of areas
6,12	0,56087201	6,12	0,69874402	6,12	0,86389093
7,62	0,53119672	7,62	0,64820928	7,62	0,77675868
9,12	0,5141524	9,12	0,61390925	9,12	0,71344015
10,62	0,51459242	10,62	0,59920513	10,62	0,67274993
13,12	0,59848189	13,12	0,65902425	13,12	0,69075353
14,62	0,71410155	14,62	0,75608257	14,62	0,75853994
16,12	0,88154696	16,12	0,89297723	16,12	0,8563545
17,62	1,13452787	17,62	1,08724582	17,62	0,98942425

MIRROR 4		MIRROR 5		MIRROR 6	
Time	Ratio of areas	Time	Ratio of areas	Time	Ratio of areas
6,12	1,02398451	6,12	1,14090087	6,12	1,20939418
7,62	0,88047836	7,62	0,92766533	7,62	0,92473368
9,12	0,77659574	9,12	0,78095812	9,12	0,74370376
10,62	0,70195303	10,62	0,67478593	10,62	0,61774384
13,12	0,66816213	13,12	0,59882422	13,12	0,51729964
14,62	0,7028559	14,62	0,60765363	14,62	0,5112133
16,12	0,76191456	16,12	0,63824431	16,12	0,52530559
17,62	0,84312067	17,62	0,68488888	17,62	0,55233946

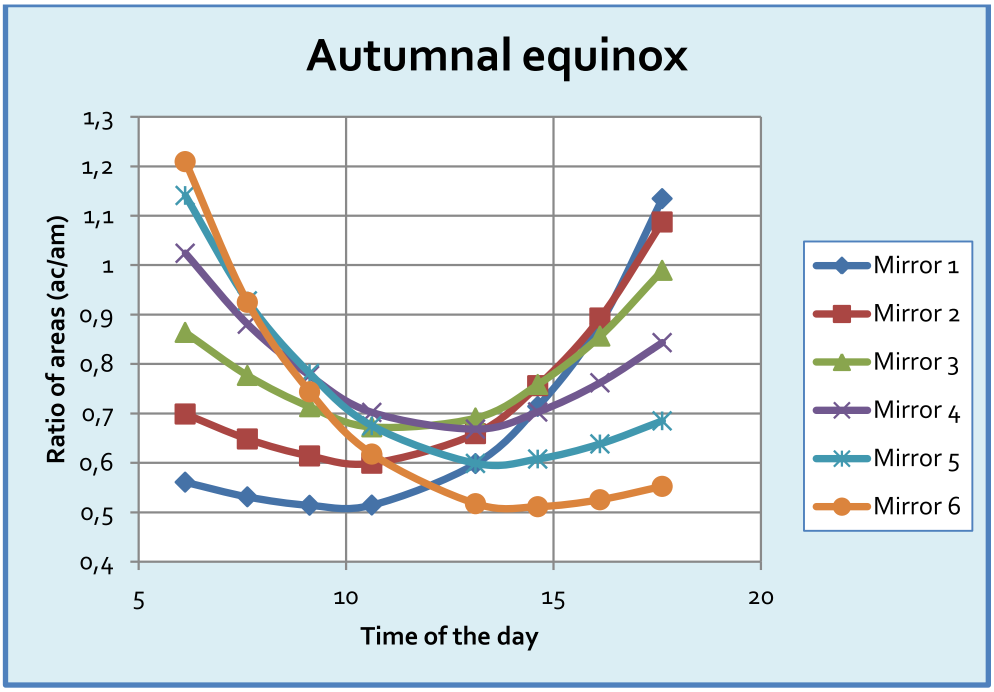


Figure 34 Autumnal equinox ratio for every mirror of the concentrator

At the beginning of the day, the mirrors that have the higher ratio are the ones placed at the right hand side of the installation, this is because they are situated in the west while the first three mirrors are in the left, the east. Because of this, the mirrors on the right part concentrate in a better way the sunlight.

Due to the same reason, the mirrors placed in the eastern part, left hand side, have the higher ratio at the last hours of the day.

In general, and, as it has happened in the previous cases, the behaviour of all the mirrors is symmetrical, as it is the geometrical disposition of the facility.

One of the most important aspects is that at midday, when the solar radiation is the highest, the conversion of the mirrors is the worst of the whole day. The prototype has better ratios early in the morning or late in the afternoon, but in these moments; the intensity of sunlight arriving to the installation is not as much as at noon.

4.1.4. Winter solstice

In contrast to the summer solstice, the winter solstice has a longer night than day. It is the December, 21st with the shortest duration day.

The data taken from the drawings are the following ones:

Table 4 Winter solstice ratios for the six mirrors of the concentrator

MIRROR 1		MIRROR 2		MIRROR 3	
Time	Ratio of areas	Time	Ratio of areas	Time	Ratio of areas
7,87	0,55933582	7,87	0,69614823	7,87	0,85930765
9,37	0,52760801	9,37	0,64167056	9,37	0,76494377
11,11	0,51293713	11,11	0,59992811	11,11	0,67861632
12,37	0,55795865	12,37	0,62624611	12,37	0,6712602
13,87	0,72112533	13,87	0,76197463	13,87	0,76275976
15,37	0,95837539	15,37	0,95348078	15,37	0,89870301
16,37	1,1580343	16,37	1,10839144	16,37	1,00340729

MIRROR 4		MIRROR 5		MIRROR 6	
Time	Ratio of areas	Time	Ratio of areas	Time	Ratio of areas
7,87	1,01627515	7,87	1,12898698	7,87	1,19268804
9,37	0,86139272	9,37	0,90033966	9,37	0,89026082
11,11	0,71432509	11,11	0,69329529	11,11	0,63915837
12,37	0,66704289	12,37	0,60841787	12,37	0,53405614
13,87	0,70530441	13,87	0,60876373	13,87	0,51155497
15,37	0,78788155	15,37	0,65304294	15,37	0,53364972
16,37	0,85154273	16,37	0,68978976	16,37	0,55526727

As it can be seen the last hour at which the simulation finishes is earlier than for example in summer, this is, at was explained above, that the fewer amount of hours of daylight. From these data, the following graphic is obtained:

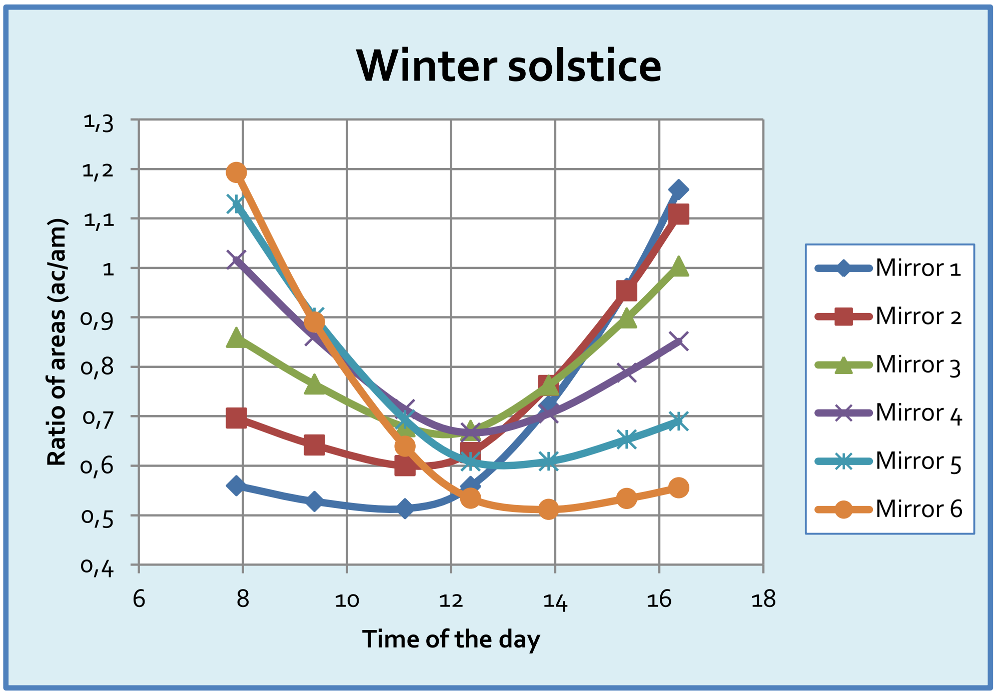


Figure 35 Winter solstice plot of the mirrors' ratios.

Winter solstice is the day of the year that has less hours of sunlight and also the solar inclination is very low, so it is day in which it is expected to have the worst behaviour and, besides the less amount of electricity produced.

As in the previous cases, the general performance is symmetric respect to the vertical axis crossing the middle point of the panel. And, the tendency of the curves is similar varying the value of them.

For all the four cases analysed, the minimum value the ratio takes is 0.5 and the upper limit is 1.2. So the concentration factor at least is of the 50 %. When the ratio takes values greater than 1 this means that the reflected area is smaller than the panel effective area. In this case, the totality of the panel width is not hit by the reflected light. This implicates that the current configuration of the prototype is not the most efficient because it is not able to match the minimum requirement, as it will be explained later in section 4.2.

4.1.5. Mirror analysis

Another way to analyze the behaviour of the facility using the same data as before is plotting each mirror separately for the four days. So, it is easier to see how the mirrors work.

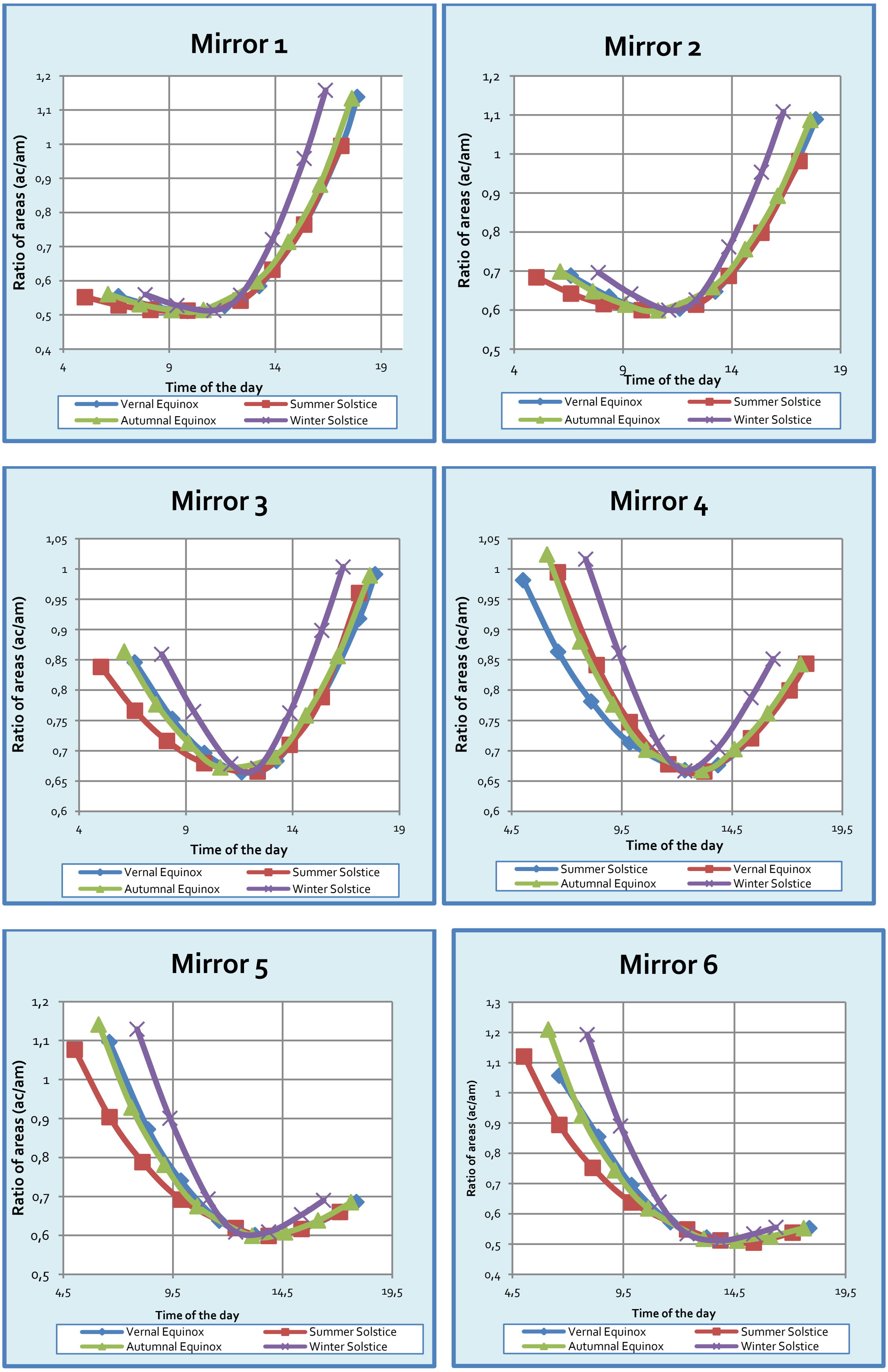


Figure 36 Compilation of graphics of all the mirrors behaviour at the four analysed days

From these six graphics important information can be extracted. Since the facility has a symmetric configuration it is natural thinking that it will have in such a way a symmetrical behaviour and so it is. The three left hand side mirrors are exactly symmetrical to the three right hand side mirrors. Knowing that the sun rises in the west, right part of the installation at the frontal view, and sets in the east, left part ; mirrors at each part, have opposite ratio to the symmetrical one. That is to say, mirror 1 has, for instance, early in the morning the same ratio that mirror 6 late in the afternoon. The same happens with mirror 2 and 5; and also with 3 and 4.

The first three mirrors, left hand side, have the maximum ratio at the end of the day, contrary to what happens to mirrors 4, 5 and 6, that reach the maximum values in the morning.

It is also interesting the fact that the mirrors 3 and 4 are the ones that have the more symmetrical behaviour, but not among them. The ratios at the beginning and at the end of the day are very similar. That leads to an almost parabolic wave of the ratio, reaching the minimum value at midday. This is due to the sun rays hitting the mirrors very perpendicular, so the effective area of them is bigger than the PV panel's, making the ratio smaller. It is shown in the following figure:

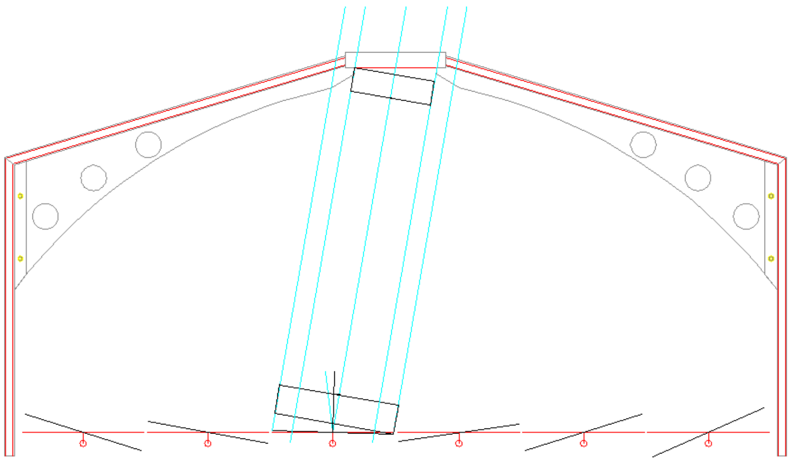


Figure 37 Cad drawing for winter solstice at midday for the third mirror

Now, it is easy to see that the projected sunlight area by the mirror is quite larger than the effective area of the panel; so, there is a waste of available energy the facility is not converting into electricity.

4.2. Matlab ratio

In this part of the study a mathematical model has been developed in order to calculate the energy loss, which is the reflected flux of energy not hitting the panel, due to geometrical reasons. The development of the software will allow to improve and optimize the configuration of the installation.

To determine the amount of reflected non incident energy on the panel is enough to verify the only theoretical condition that follows:

Equation 21

Where,

is the projection of the receiver panel width on the perpendicular plane with the panel-mirror join.

is the projection of the side of the mirror on the perpendicular plane with the panel-mirror join.

With this condition, the ratio is being calculated and it is supposed to be the same that the one obtained graphically by means of Autocad. If they are the same, the mathematical model will be verified.

To analyse this condition inside the configuration, the problem should be splitted in two, the three mirrors on the left hand side (mirrors 1,2 and 3) and the mirrors on the right hand side (mirrors 4,5 and 6). Besides, in order to analyse them, the morning and the afternoon should be considered separately. So, in the end, there are four different cases to analyse.

Notice that the red lines in the following figures correspond to the reflected solar rays. The main objective is to express the ratio as a function of the angles already known, that is, express the incident angle, i, as a function of the rest of angles.

In order to apply this condition appropriately to the geometry, the problem should be divided into four cases.

Case 1

In this case the first three mirrors in the morning are analysed.

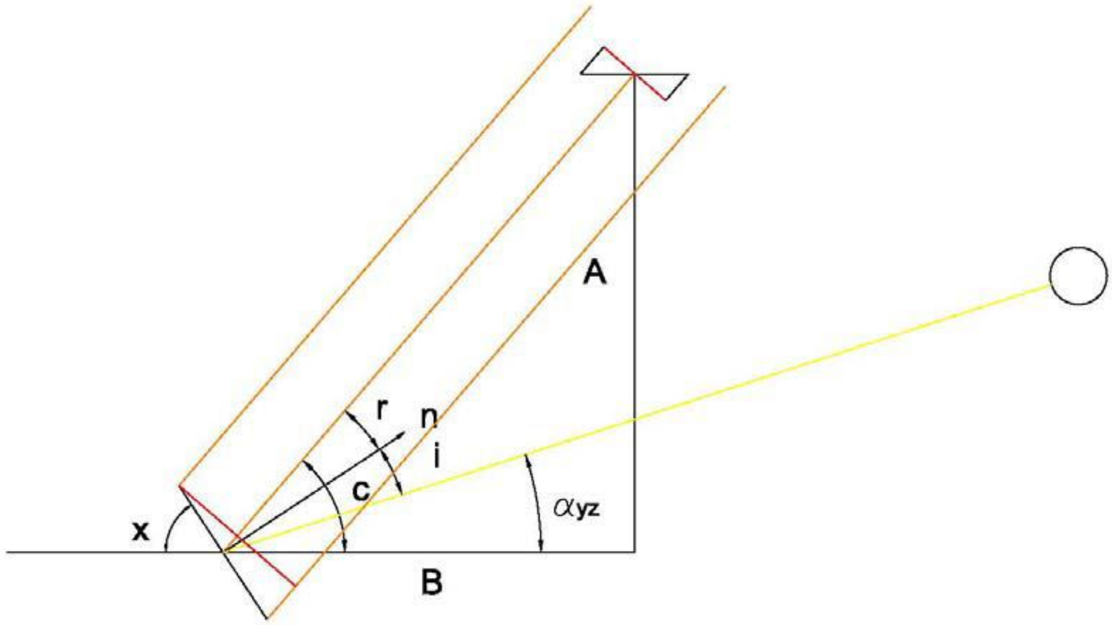


Figure 38 Energy loss. Case I

From Figure 38, the following information is obtained:

Equation 22

So that,

Equation 23

Finally, the condition to verify is:

Equation 24

From this equation, the expression for the ratio, implemented in Matlab results of the way:

Equation 25

In this way, the available area from the panel is compared to the reflected from the mirrors.

Case 2

In this case, the right hand side mirrors are analysed, considering the morning situation.

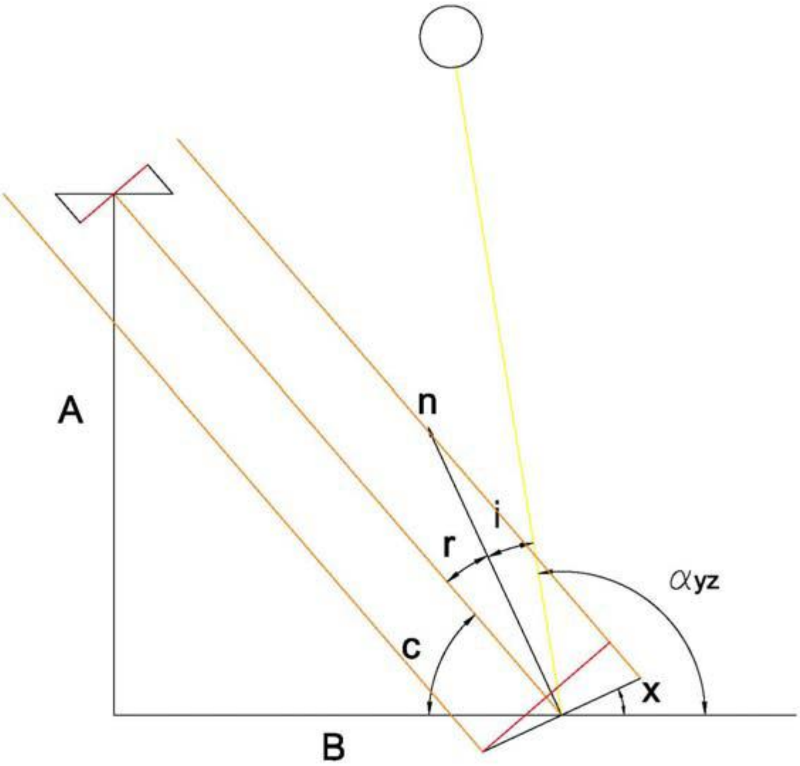


Figure 39 Energy loss. Case II

From Figure 39, the following information is obtained:

Equation 26

So that,

Equation 27

Finally, the condition to verify is:

Equation 28

From this equation, the expression for the ratio, implemented in Matlab results of the way:

Equation 29

In this way, the available area from the panel is compared to the reflected from the mirrors.

Case 3

Now, for the mirrors on the left hand side, the afternoon case is studied.

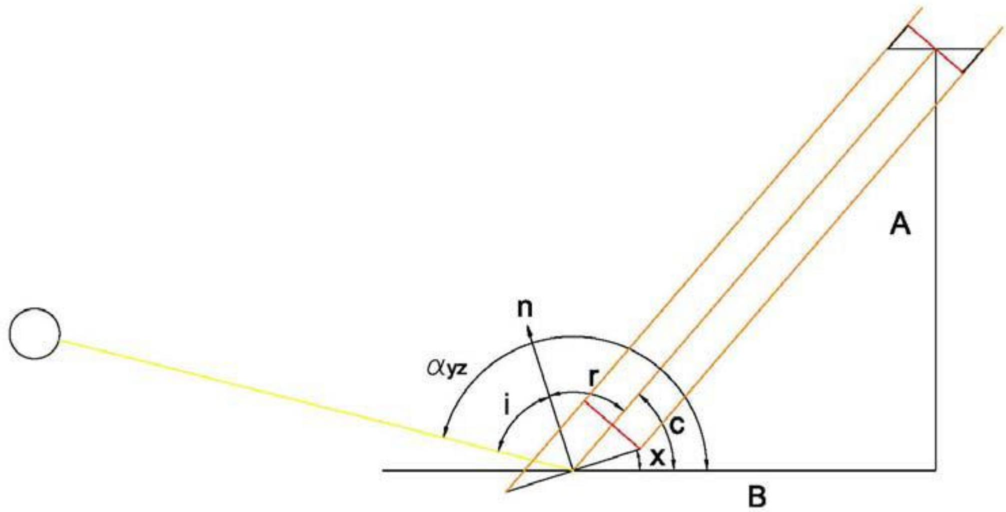


Figure 40 Energy loss. Case III

From Figure 40, the following information is obtained:

Equation 30

So that,

Equation 31

Finally, the condition to verify is:

Equation 32

From this equation, the expression for the ratio, implemented in Matlab results of the way:

Equation 33

In this way, the available area from the panel is compared to the reflected from the mirrors.

Case 4

The case 4 corresponds to the afternoon situation for the last three mirrors.

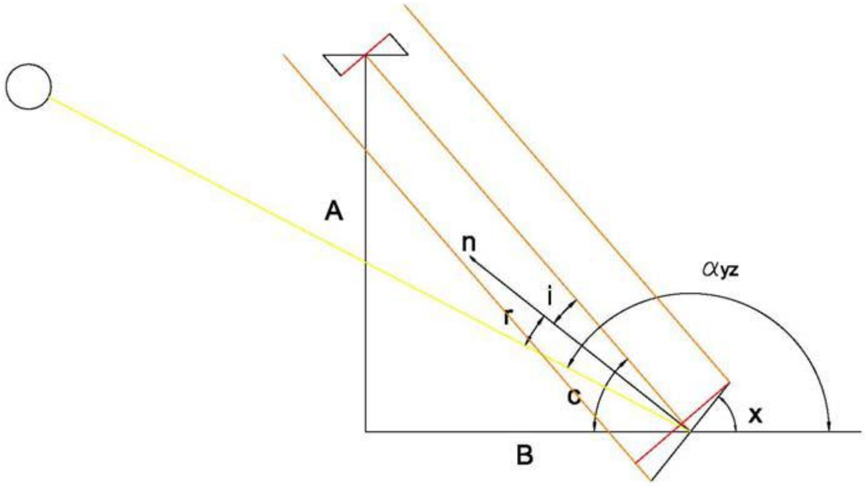


Figure 41 Energy loss. Case IV

From Figure 41, the following information is obtained:

Equation 34

So that,

Equation 35

Finally, the condition to verify is:

Equation 36

From this equation, the expression for the ratio, implemented in Matlab results of the way:

Equation 37

In this way, the available area from the panel is compared to the reflected from the mirrors.

In the Annex 1 the Matlab program developed for the computation of the ratio is attached.

Let's explain briefly the meaning of the different values the ratio can take. There are three possibilities found:

If the ratio is between zero and one, this means that the projected area from the mirror is bigger than the available one from the cell; but, in any case, the total panel is covered by the projected sunlight.

If the ratio is zero, there is no sunlight hitting the panel. This case is being erased from the computation because the target is analysing the cases when it does not take null values.

And, when the ratio is greater than one the panel area is bigger than the reflected from the mirrors. This is the worst case in which the installation can be found because of the working capacity of the photovoltaic panel. The current flowing through the panel is given by the smallest one of all the cells that composes it. For this reason, when only some of the cells are hit by the sunlight, and other are not, the current will be highly limited. This is the most undesirable situation.

In general, it can be said that the most interesting situation is the first one since the whole panel surface is hit by sunlight but, not in an effective way because the facility is wasting energy that could be transformed in electricity.

Apart from exporting all the data computed in order to verify the model, as it will be explained in the next section, the ratios have been also calculated in order to analyse the general behaviour of each mirror along the year, not just four isolated days as it has been done with AutoCad. The program developed in Matlab has helped in the tedious calculation of them because of the huge amount of calculations needed. In order to understand better all the values obtained, they have been exported to an Excel file to plot some graphics.

There are different ways of plotting the huge amount of information extracted from the evaluation of the program. To simplify all this data, the program was only run in steps of one hour. Every day of the year, at every hour but at the same minute (minute 37).

In this report the graphics of each mirror are only shown.

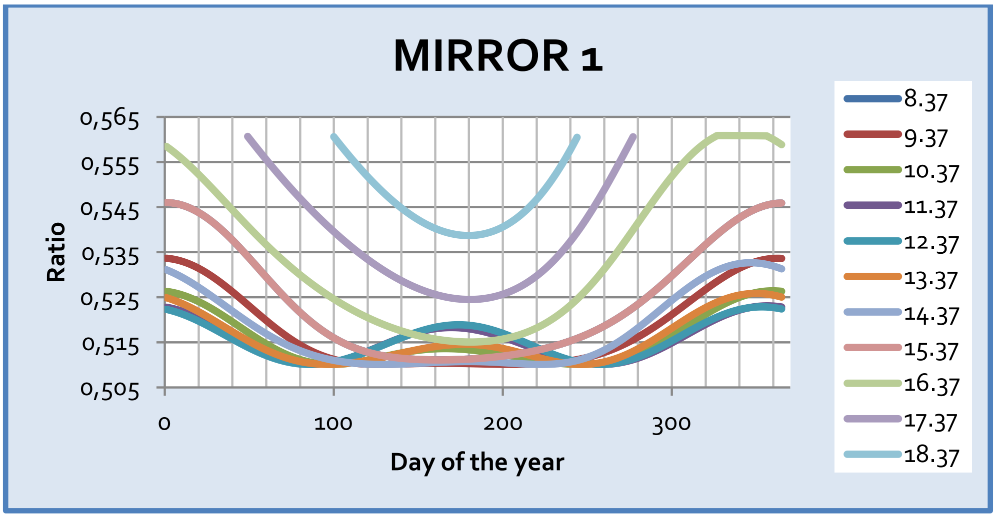


Figure 42 Ratio of mirror 1 along the year for every hour of the day

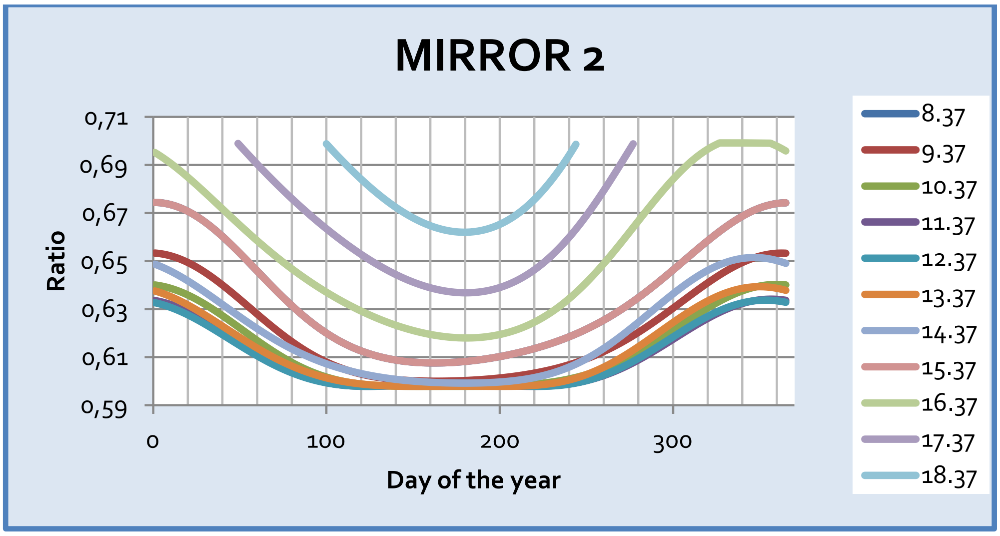


Figure 43 Ratio of mirror 2 along the year for every hour of the day

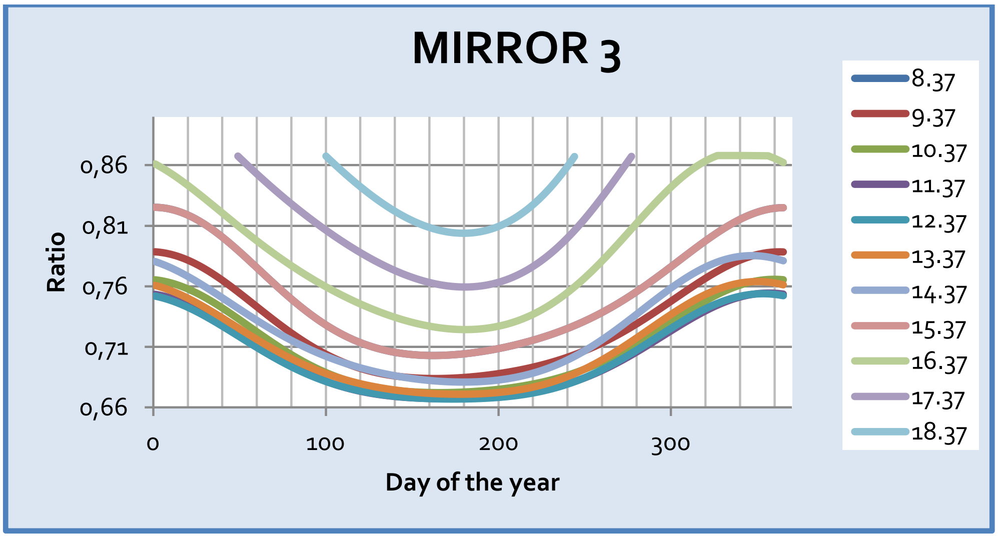


Figure 44 Ratio of mirror 3 along the year for every hour of the day

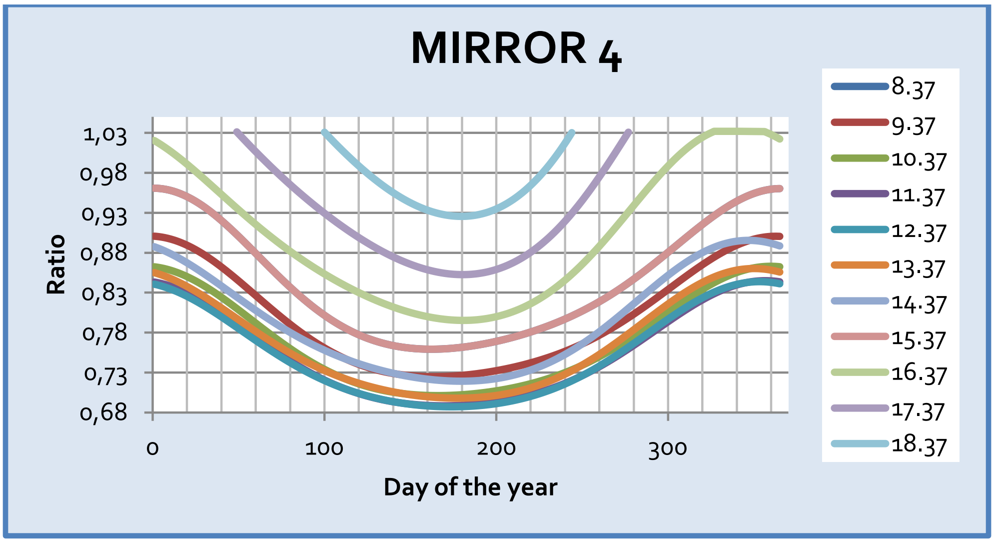


Figure 45 Ratio of mirror 4 along the year for every hour of the day

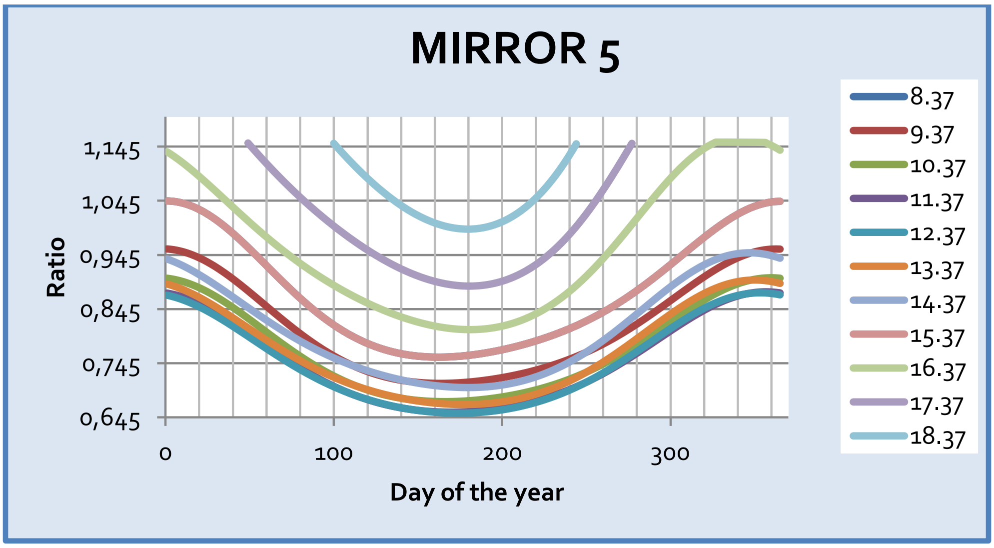


Figure 46 Ratio of mirror 5 along the year for every hour of the day

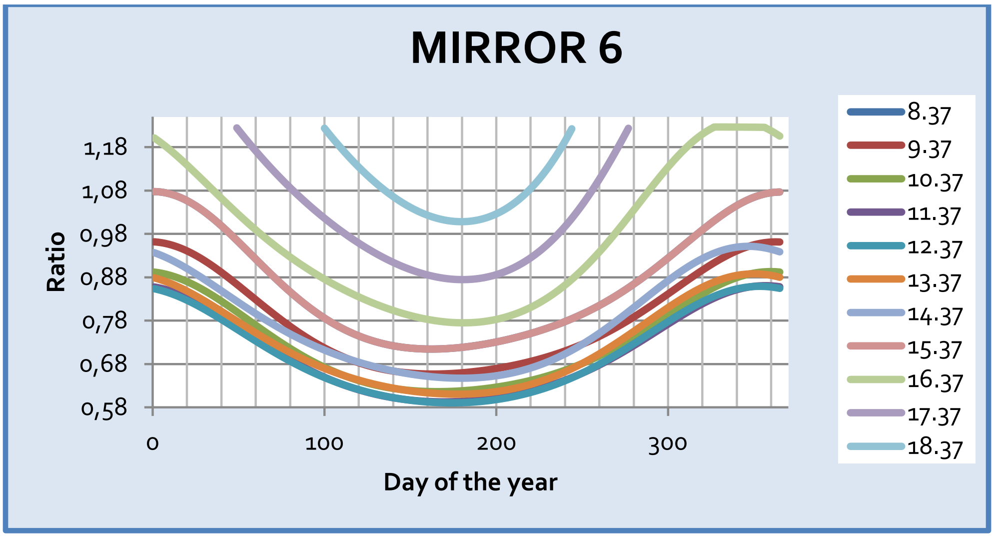


Figure 47 Ratio of mirror 6 along the year for every hour of the day

As it can be appreciated in the six graphics shown before, the general behaviour of the mirrors along the year, for every hour of the day is almost the same; but, depending on the time of the day, the value of the ratio changes. For all of them, the ratio is always bigger at 5 and 6 pm in the afternoon. By the contrary, it takes the smaller values at midday; which means that when there is the higher irradiation of the day, the configuration of the facility cannot achieve the maximum of it.

It is also interesting analyse the fact that the ratio takes the smaller values in the spring and summer months. In these seasons the sunlight arrives with higher intensity than in the rest of the year so, for this reason in that period the facility should produce more energy.

It is also interesting to comment the fact that the ratio, for the latest hours of the day, as it was said, takes the greater values but, besides, for the mirrors on the right hand side (mirrors 4, 5 and 6) they are bigger than one. This means that the panel area is not covered in its totality. So, the ratio takes bigger values than in the rest of the day but, not in the desired situation.

4.2.1. Validation of the mathematical model

In order to verify that the model explained in the previous section is correct, the days geometrically analysed by means of AutoCad were checked by hand. A matrix with the corresponding ratios was imported from the Matlab program written. The computation of the ratios was done for every mirror, for a time step of 15 minutes, but only for the period of time that has sunlight during the day.

By this light prove, the model developed was correctly satisfied for each one of the four days analysed resulting a difference in the ratios from the fourth decimal; so the model can be said to be correct.

4.2.2. Annual energy calculation

One variable that is also interesting to analyse in order to have a brief knowledge of the amount of energy the facility is able to pick up, is the total annual energy. The received energy from the mirrors is transformed into the actual energy collected at the photovoltaic panel through the ratio. That is why it has been computed, because it behaves as an efficiency of the concentrating capacity of the prototype.

In order to calculate the energy, an already developed program of Matlab was taken as a sample and modified to adequate it to this particular situation.

To be able to calculate total solar flux at any clear day, the addition of the direct, diffuse and reflected solar radiation on the ground; an semiempirical model reference of the 'atmosphere' can be done, allowing a sophisticated degree of accuracy. The most used mathematical model is the ASHRAE, based on the normal and diffuse radiation calculation through the appropriate relationships. [24]

A is the *extraatmospherical radiation*, whose origin is the zenithal rays. It is measured everyday of the year through:

Equation 38

B is the *extinction coefficient of the atmosphere*:

Equation 39

For our particular case, the diffuse energy will not be taken into consideration for simplicity reasons.

Knowing how to calculate the amount of energy arriving to the facility and adjusting the sample given in [24] to this specific problem the total annual energy arriving to the photovoltaic panel can be easily computed.

The program developed in Matlab is attached in Annex 1. The result this software provides for the current design of the installation is:

Equation 40

Actually, this isolated value does not provide much useful information but it will be a reference when different tests will be done.

4.3. Variation of the ratio

As it was commented before, the ratio and the total energy calculation has a main scope the comparison with other values changing the main geometry of the installation. With changing the geometry means the variation of the dimension of the mirrors and the panel. In this way the total energy can be an important variable to know if the efficiency of the prototype is being improved or not.

4.3.1. Change of the width of the cell and the mirrors

The choice in the variation of the cell cannot be done randomly because its width is fixed by the manufacturers. Since the company has decided to change it from 29 cm, which is the current dimension, to 55 cm; this modification is going to be analysed.

By the contrary to what happens with the cell, the width of the mirrors can be changed in the company where the prototype is being constructed. Without modifying the total width of the facility, the width of each mirror can be changed, that is, reducing their dimension.

For this reason this study has been developed together because the variation in the width of the panel is been fixed so, in general terms, there are two main cases to analyse and, inside them, several possibilities with the mirrors' dimensions.

For simplicity, all cases in which the ratio was bigger than 1, it would be changed into 1. With this change and exporting the data to a excel file, all the moments in which the cell is not filled at all by the concentrated sunlight would be easily identified.

Now, all the cases analysed will be discussed:

- $e_c = 29\ cm$

This is the current dimension of the photovoltaic panel, fixing it, the width of the mirrors are modified in order to see how the ratio and, therefore, the total annual energy, change. The total width of the installation is fixed, although the width of the mirrors is decreased. This fact makes that the gap between mirrors is increased.

Case 1: em=29 cm

Making them equal it is obtained that more or less the 50 % of the ratios computed for all the year, every fifteen minutes, are equal to 1. This means that, the 50% of the time, the panel is not completely hit by the reflected rays from the mirrors.

Case 2: em=32 cm

In this case, the simulation provides that at least 30 % of the calculated ratios were equal to 1. So, compared to the previous case, there is an improvement but there is still a problem of losses because of the limitation of the current when the whole panel is not covered by sunlight.

Case 3: em=36 cm

This case has less values equal to one, but compared to the case 2 it has more values smaller than 1. As a whole, the global efficiency is worse than the previous one.

Case 4: em=39 cm

This is the real configuration of the facility. Running this case, it is the one that has fewer values equal to 1 but it is also the one with the worst efficiency because there are a lot of ratios smaller than 0.5; which is a really low value.

Now the results from the software are represented in the following graphic.

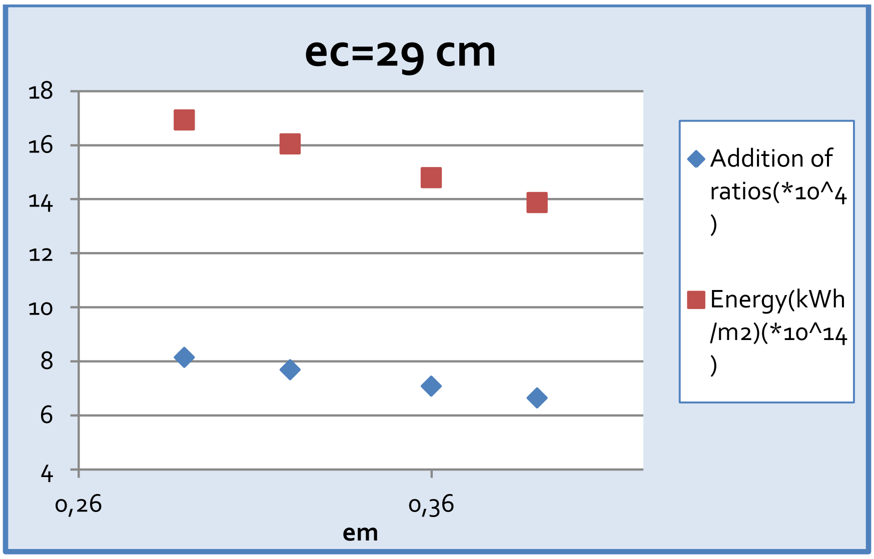


Figure 48 Behaviour of the facility varying the width of the mirror for the first design

As it is easily identified, the general tendency of the installation is that, fixing the panel width, as the mirror width is being increased, the total addition of the ratios (along the year) and the total energy reached, per unit area, decrease linearly.

- e_c=55 cm

This width for the panel corresponds to the new one configuration that will be implemented by Metalmeccanica Pulsoni. For this reason it will be analysed. Compared to the previous analysis the total width of the facility will be varied, it won't be fixed, as it has happened before.

Case 1: em=39 cm

This configuration corresponds to the future one that will be implemented. By running the simulation in Matlab the Excel file obtained with the ratios shows a high amount of values equal to one. So, there is not any improvement respect to the previous design. Although the addition of all the ratios, for the whole year, is bigger; the current flowing through the cells, due to the fact that they are in series connection, will be smaller.

Case 2: em=55 cm

Trying a new way, with making both widths equal, the total width of the facility would have to be increased too. The addition of all ratios and the total energy per unit area is smaller than in the previous case but the total energy computation is bigger.

Case 3: em=45 cm

Keeping the total width of the case 2 but decreasing the width of the mirrors, that is, increasing the gap between them, it is obtained that there are more losses because the average of the ratio value has decreased. On the other hand, the total energy per unit area has been improved.

Case 4: em=45 cm

Decreasing the gap between the mirrors but maintaining the width of the mirrors it is obtained that this configuration is better than the previous one because there are less losses. So, the total energy and the addition of the ratios, is bigger.

As before, the results obtained by running the program developed in Matlab are plotted.

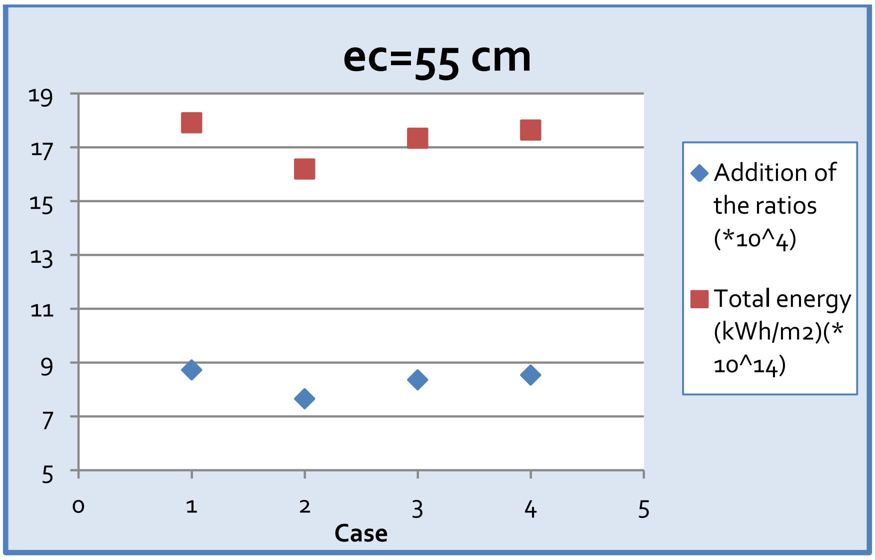


Figure 49 Behaviour of the facility varying the width of the mirrors with the new panel

In this case, the behaviour of the both variables analysed, do not follow the same tendency as in the previous case. Since now the total width of the structure is changing with the mirrors but not in the first study.

4.3.2. Change of the height of the cell

Another parameter to analyse is the variation of the height at which the photovoltaic panel is placed respect to the mirrors. In order to do this, the whole structure of the prototype should be changed but its effect on the efficiency is interesting to be considered.

Although the values of the energy are not exactly the correct ones because of some simplifications taken, what really interests the study is the general tendency of its variation. In the following figure it is shown:

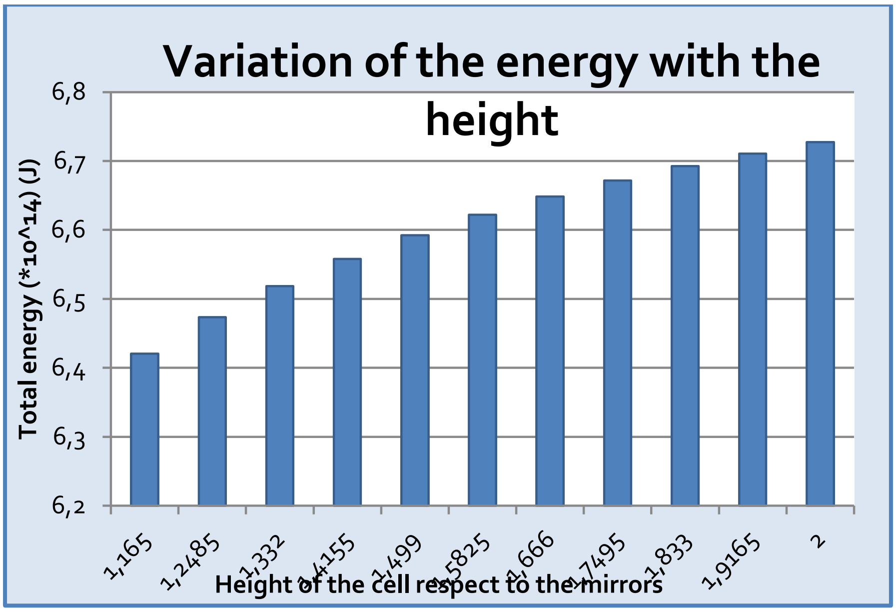


Figure 50 Behaviour of the installation varying the height of the panel

As it can be seen in the figure above, the general tendency is that when the height of the panel is increased, the total amount of energy that receives is also raised. This result was the expected one, since the rest of the variables have remained the same. Increasing the height, the losses are decreased and the area of the panel is filled better.

4.4. Horizontal movement of the cell

Most of the photovoltaic installations, concentrating ones also, are designed with a light inclination of the facility respect to the ground (See Figure 12). As it was explained before, for the first approach, the total length of the mirrors was determined to be greater than the panel in order to compensate the absence of the tilting inclination (β) to the sun position.

One possibility to avoid the losses because of the lack of tracking to follow the sun path along the year due to the inclination of it respect to the ground, is a horizontal movement of the photovoltaic panel is suggested.

In order to know the possible motion of the panel along the year, four days have been analysed. As in the first section, the two solstices and equinoxes since they represents the days with the higher and lower inclination of the sun respect to the ground.

In the following figure, the four cases are shown regarding that they represent the noon of each one of the days.

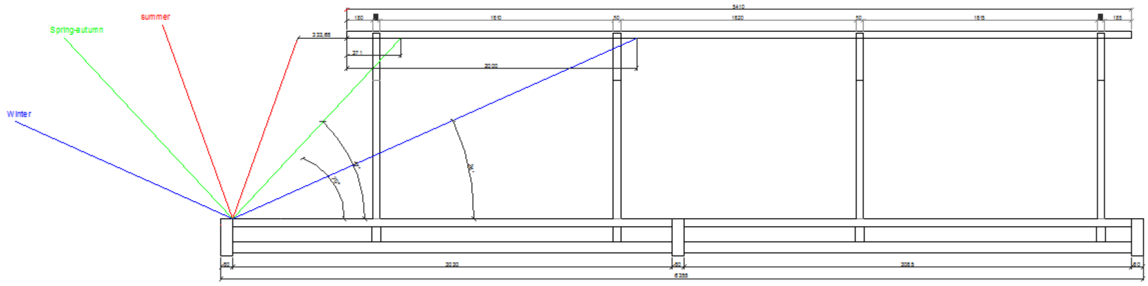


Figure 51 Horizontal movement of the panel. Analysis for the equinoxes and solstices.

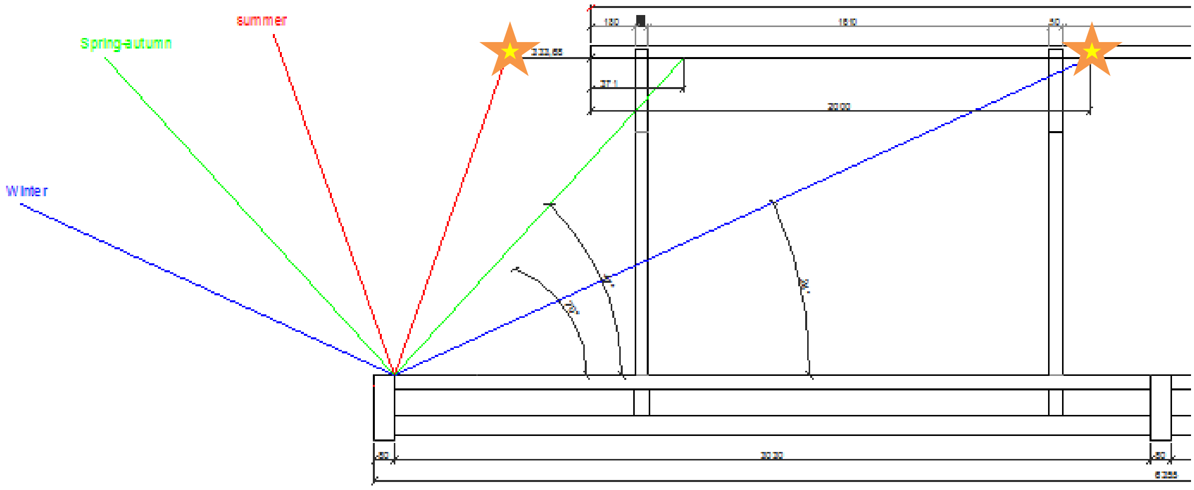


Figure 52 Zoom of Figure 51. Horizontal movement of the panel

From the first sunray that hits the mirrors at winter (blue line), it is seen that there is a total length of the panel equal to 2m that are not hit by the reflected light. The installation is wasting an available area because of the design hat could be used in the rear part of the facility. From the first sunray that hits the mirrors in summer (red line) it is concluded that it is out of the panel. The first reflected ray is placed 33 cm from the panel. So, if the configuration was optimum, this area could be exploited. Both equinoxes are placed in a middle point, always hitting the panel so the important cases are the first ones.

As a result from this simple study, the minimum and the maximum limits for the photovoltaic panel in order to take advantage of the reflected energy in a better way are fixed. The range in which it should be moved is being set but the main disadvantage is how to do it. The implementation of a tracking system is very costly and it possibly does not worth it compared to the efficiency improvement achieved. Other possibility could be the manual movement for each season. The increase in the efficiency would not be the same, but in any case, it would be enhanced.

4.5. Shadows analysis

The last part of this study is the evaluation of losses in the facility due to the shadows created by the mirrors among them. The interference among them can produce a loss of the reflected light to the panel.

The analysis has been splitted into two different problems, because of the configuration of the installation; one case in the morning and the other in the afternoon. Inside each there are different situations that have been analysed and will be explained later. To carry out this study, a Matlab program has been developed and, as in previous studies, a geometrical comparison has been done by Autocad for the solstices and equinoxes.

In order to find the new expressions for the ratio, the points where the reflected sunrays cross with the height of the photovoltaic panel have been computed by means of the geometrical expressions for the lines, regarding to the reference system of the installation.

To be able to introduce in Matlab the new calculation of the value of the ratio, a study of the model for the prototype was done in which it was found different situations in which the mirrors could be found as a result of the interaction with the side ones.

4.5.1. Morning

In the morning the shadows among the mirrors can be found in four different situations. When the sun raises, early in the morning, the rotational angle of the mirrors (x) starts being negative, but while the sun starts increasing its inclination, the angle decreases until one point in which it starts growing, so, it becomes positive.

The different cases will be discriminated by the sign of the rotational angle of the mirrors.

Case 1

When both mirrors have a negative rotational angle, the ratio is calculated for the left hand side mirror (i) while the mirror i+1 is the one that is creating the shadow.

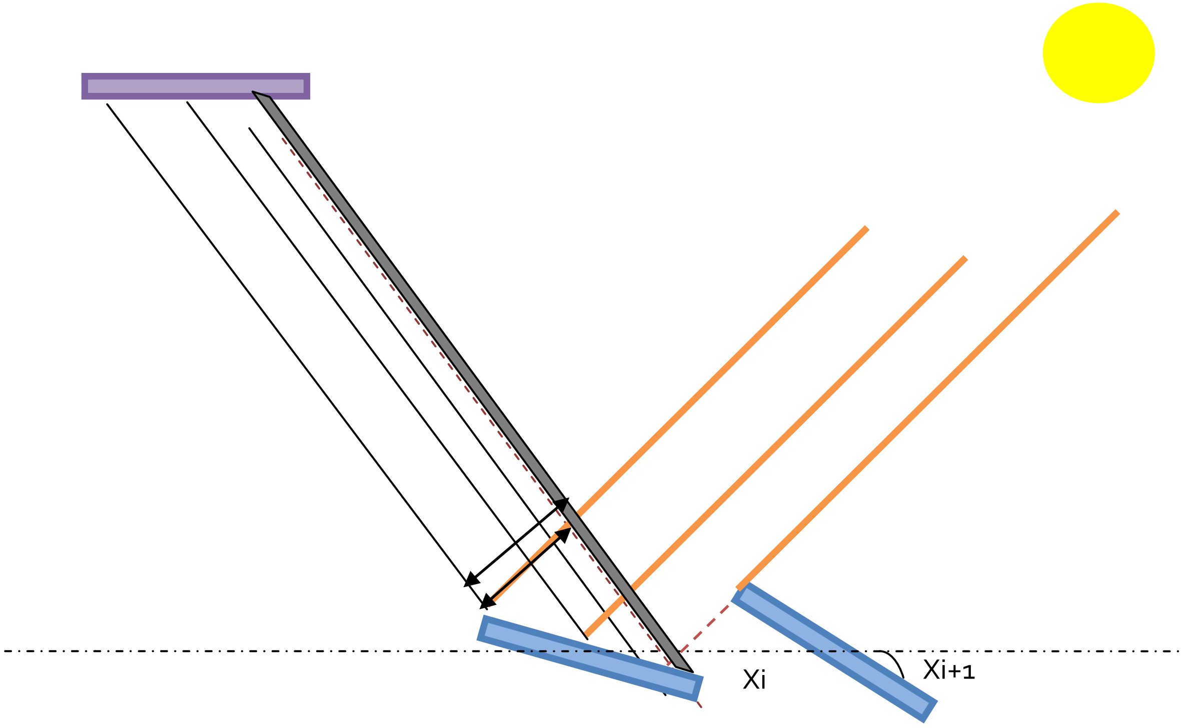


Figure 53 Case 1. Morning. Shadows description.

The grey rectangle in the previous figure represents the shadow area created by mirror i+1. This is a reflected area that was considered in previous analysis, but actually it is not arriving to the panel. The available area from the panel always remains the same; the reflected area is what is changing.

Case 2

In this situation, the angle of the considered mirror is still negative but, the right hand side mirror has changed its rotational angle to positive. The description of the model is shown in the following picture.

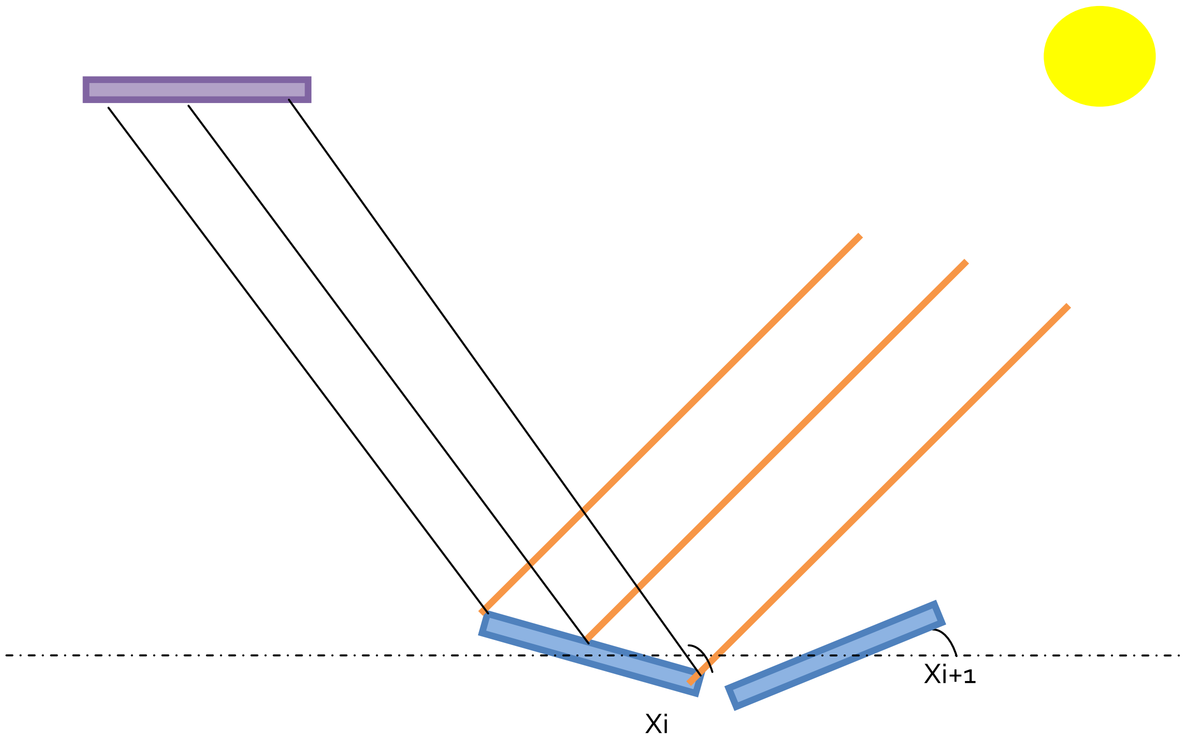


Figure 54 Case 2. Morning. Shadows description.

As it can be seen, when the angle of the right hand side mirror has become positive but the considered mirror's rotational angle remains negative, there is not any shadow created over the mirror surface. Therefore, the value of the ratio is still the one computed before.

Case 3

Finally, the last case to analyse in the morning is when both, the considered mirror and the right hand side one have a positive rotational angle. In this case, there is no shadow created over the mirror, but there is a kind of interference between them that makes the ratio to change.

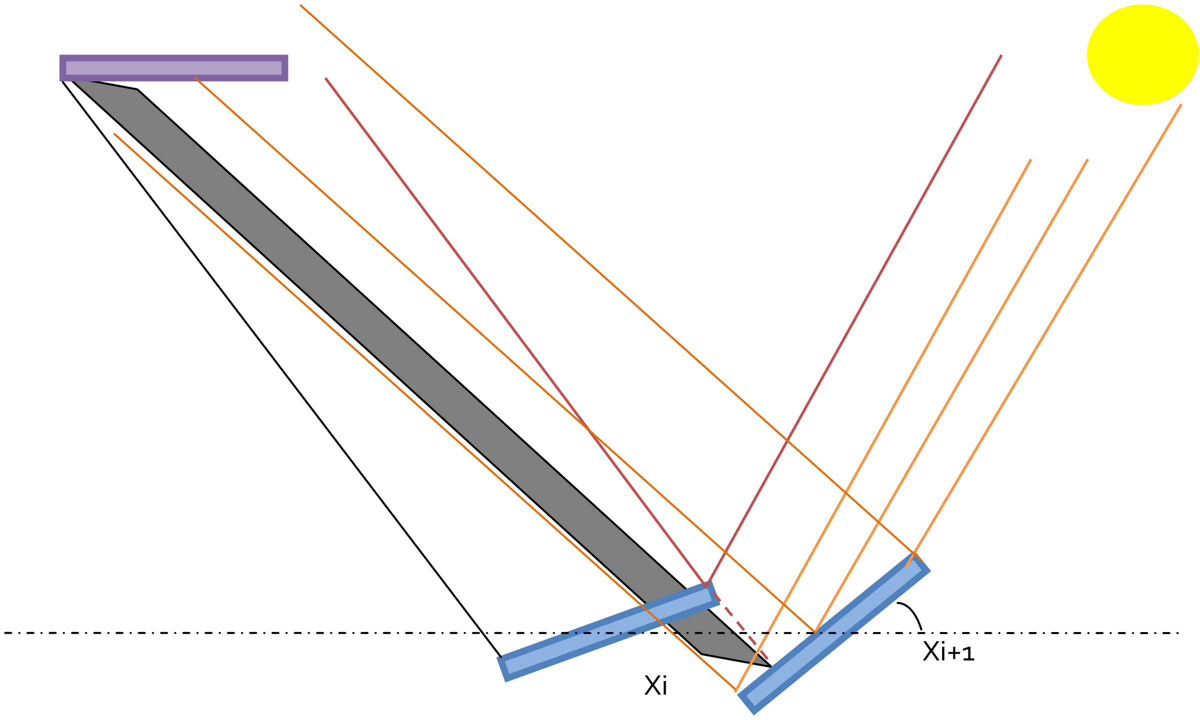


Figure 55 Case 3. Morning. Shadows description.

Now the situation has changed. As it was anticipated before, there is no shadow created over the mirror analysed (i), but, due to the configuration there is an interference of the mirror i over the reflected sunrays of the mirror i+1. Mirror i cuts the projected area of the right hand side mirror (i+1) reducing its value. As it has happened in case 1, the available area from the panel remains the same.

4.5.2. Afternoon

As it was commented before, as the inclination of the sunrays grow with the time, so do the rotational angles of the mirrors. In the afternoon, four cases have been found to be analysed. They are very similar to the ones in the morning but just changing the angles because the configuration of the facility makes the expressions for the ratio change. Now, most of the shadows are created by the left hand side mirror.

Case 1

This case corresponds to the case in which the considered mirror and the left hand side mirror have a positive value for the inclination angle. The mirror i-1 is creating the shadow in the analysed mirror (i).

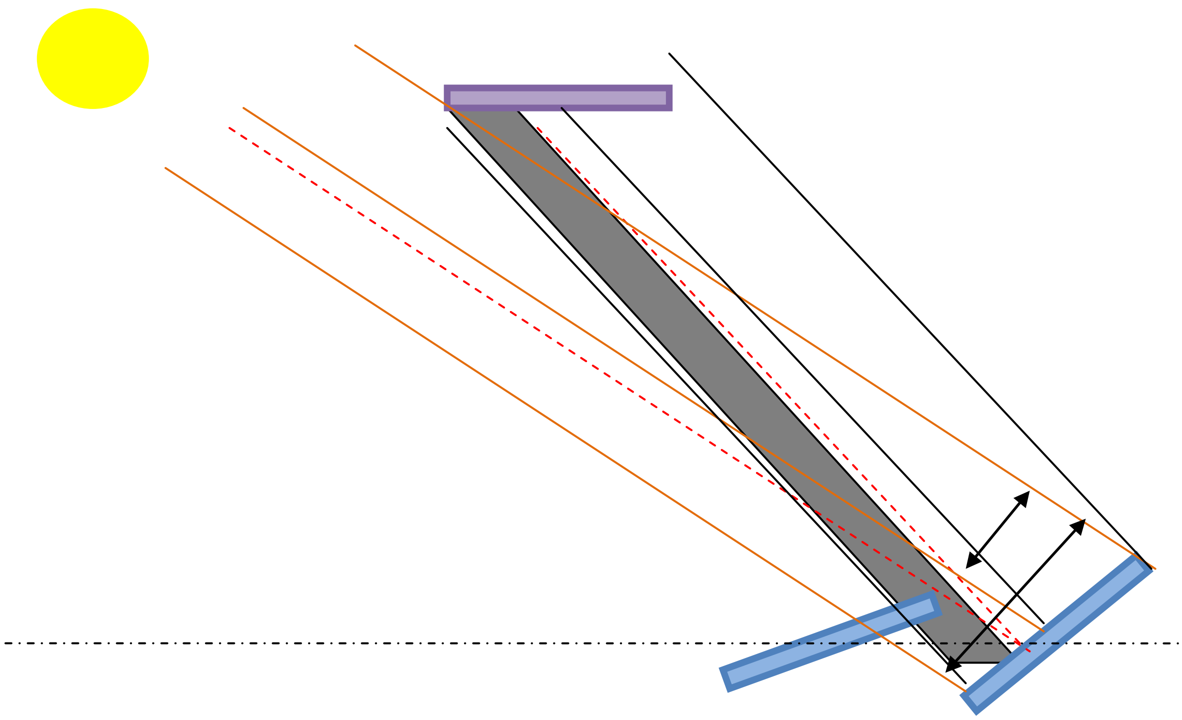


Figure 56 Case 1. Afternoon. Shadows description.

The reflected area has been reduced due to the shadow created by the left hand side mirror do while the available area from the cell does not change.

Case 2

This is the equivalent situation as the case 2 in the morning. Considered mirror has still a rotating angle smaller than zero but the mirror on its right has changed it into positive.

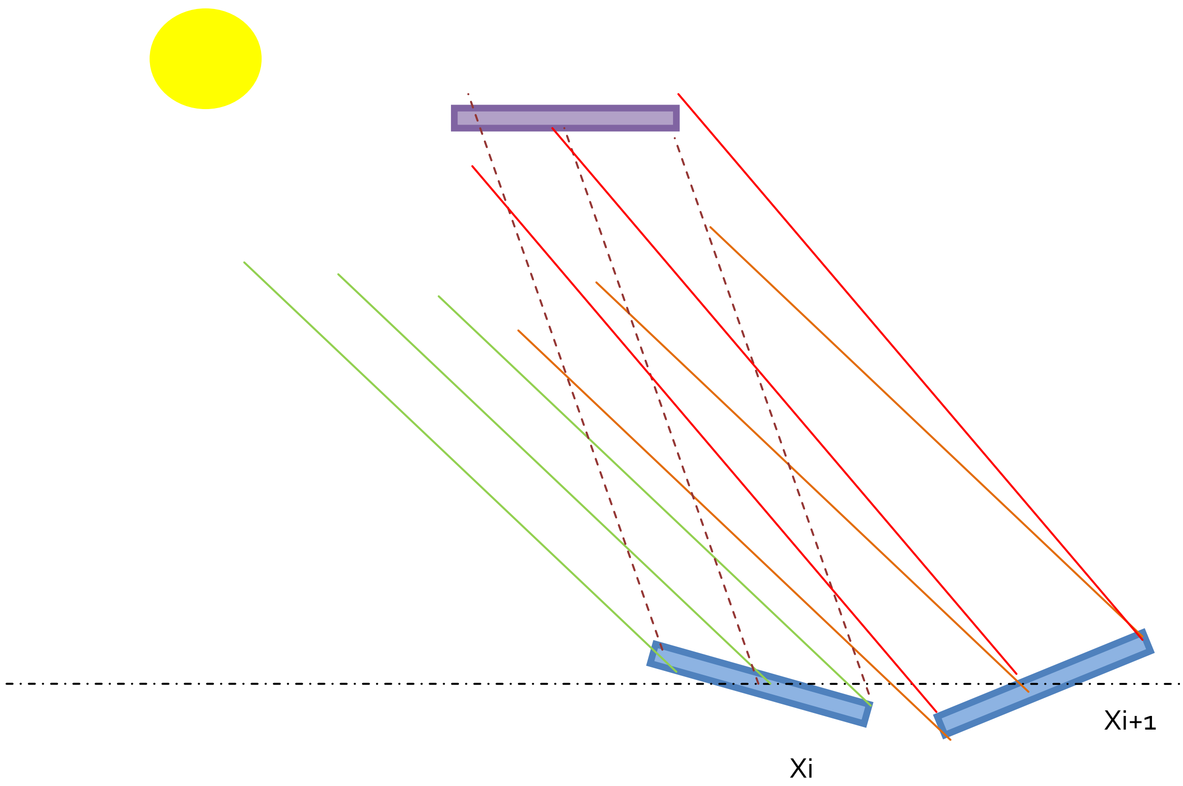


Figure 57 Case 2. Afternoon. Shadows description.

As it can be seen, in this situation, none of the mirrors interferes in the projection of the other and they do not create any shadow on their surfaces either. For this reason the ratio remains the same, that is, the calculated in the previous program without considering the shadows.

Case 3

This case is the same as case 1, in which both mirrors has a positive rotational angle but now there is no shadow created by the left hand side mirror. The situation here is that the mirror i-1 interferes in the projected area from mirror i.

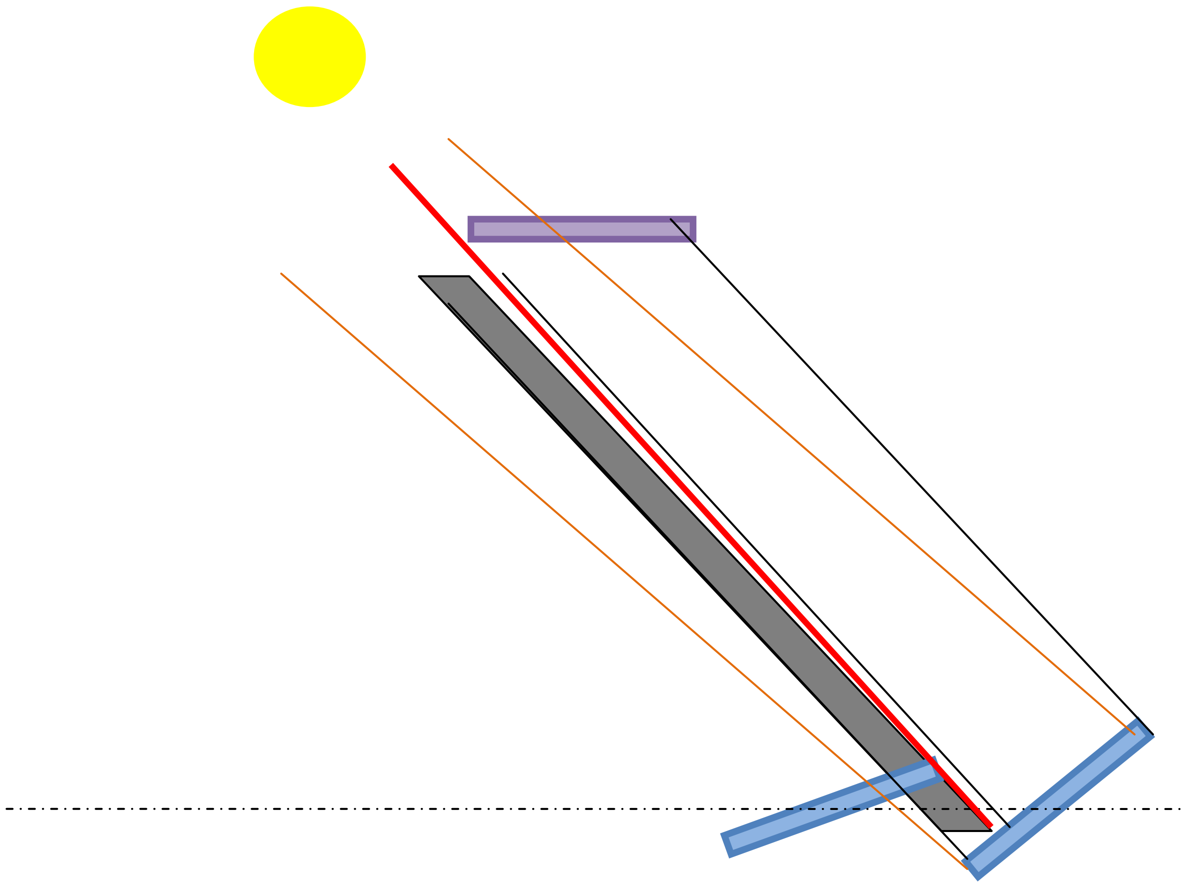


Figure 58 Case 3. Afternoon. Shadows description.

This case is the same as case 1 but with the particularity that the interference in the projected area from the mirror is greater than the shadow created, so the one that should be considered is the first one because of being the worst case since the reflected area will be smaller.

To see better this situation, a zoom at the mirrors is presented below.

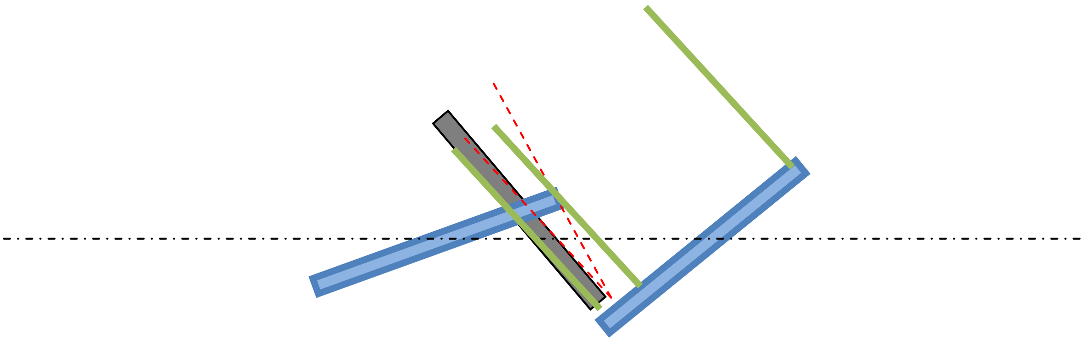


Figure 59 Case 3. Zoom. Afternoon. Shadows description.

As it can be better seen, the shadow has lees influence than the interference of the left hand side mirror on the projected area.

Case 4

Both mirrors have still a rotational angle minor than zero, as in case 1 in the morning. They have not changed yet to positive. The mirror i+1 interferes in the projection of mirror i on the panel.

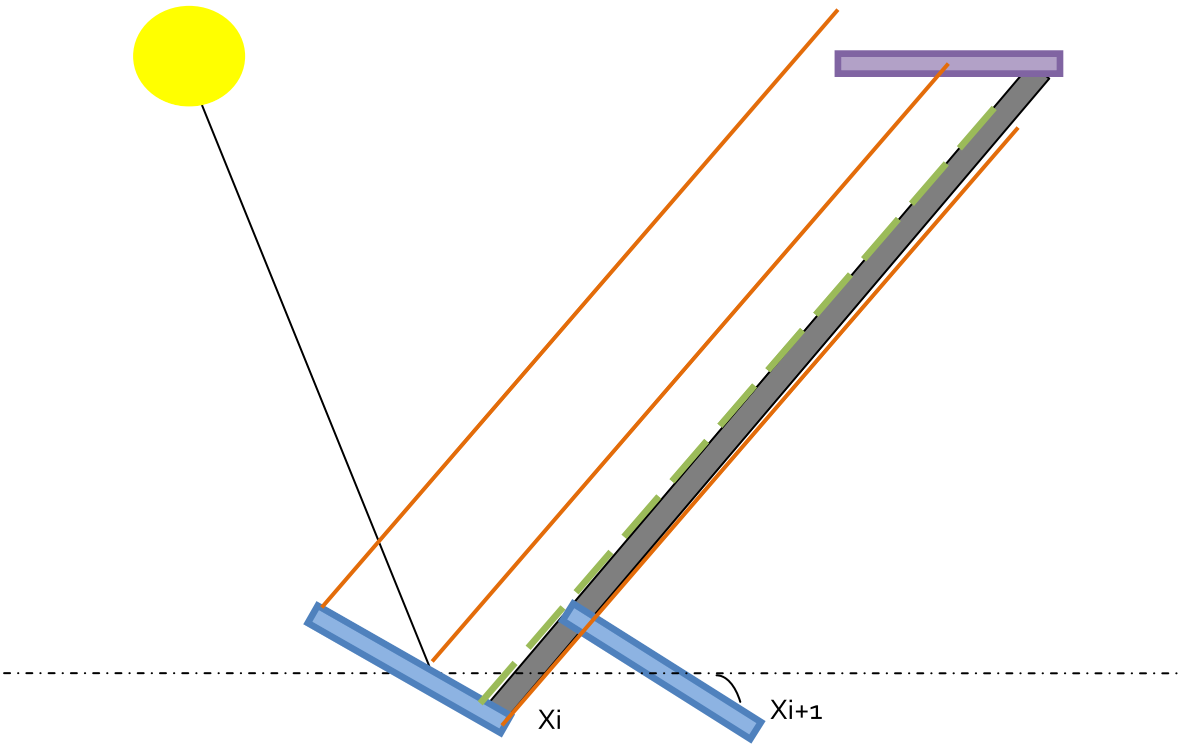


Figure 60 Case 4. Afternoon. Shadows description.

Now there is not any shadow created, just the interference from the right hand side mirror on the projected area of the mirror i; reducing the concentration on the panel.

4.5.3. Possible situations for the ratio

Due to the shadow creation or the interference of one mirror at the projected area, the ratio is changed. Because of this, the resulting concentrated area will not match the photovoltaic panel as before. For this reason, depending on the new hitting area geometry the ratio will vary its expression. The following cases that will be explained are the same for both morning and afternoon situations that has been shown before.

Case A

When both limits of the reflected area are out of the photovoltaic panel the expression of the ratio would be as follows.

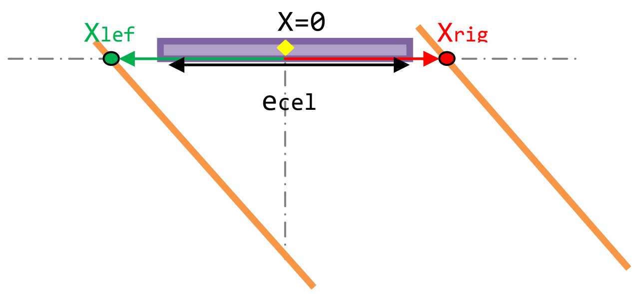


Figure 61 Ratio calculation with shadows. Case A.

The expression for the ratio in this case will be:

Equation 41

This is the same way as it was obtained without considering the shadows effect but in this case, the arriving sunrays have changed.

Case B

In this case, because of the shadows or the interference of other mirror, one of the borders of the reflected area, the left hand side one; cuts the panel in some point. So, the calculation of the ratio should be changed.

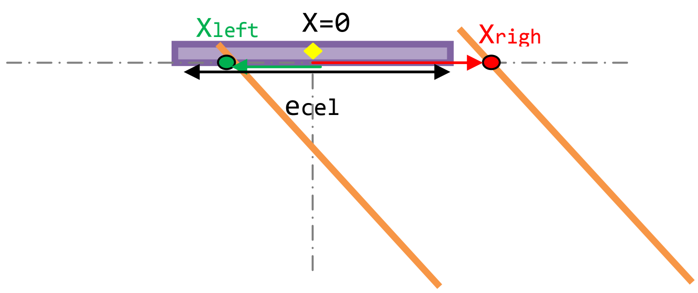


Figure 62 Ratio calculation with shadows. Case B

Now, the equation that defines the new ratio is:

Equation 42

Case C

This situation is the same as in the previous case but with the right hand side limit of the reflected area.

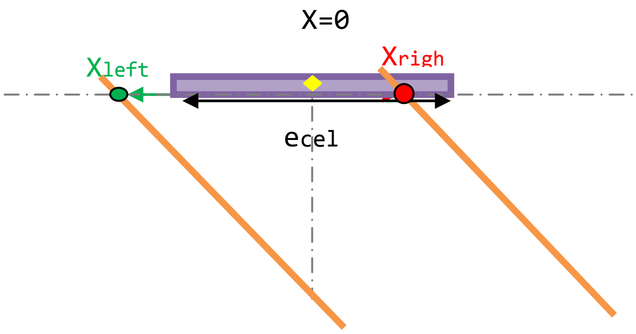


Figure 63 Ratio calculation with shadows. Case C

As before, a similar expression is the one that represents the new ratio considering the shadows effect.

Equation 43

Case D

If both bounds of the concentrated area are inside the photovoltaic panel the situation would be like this:

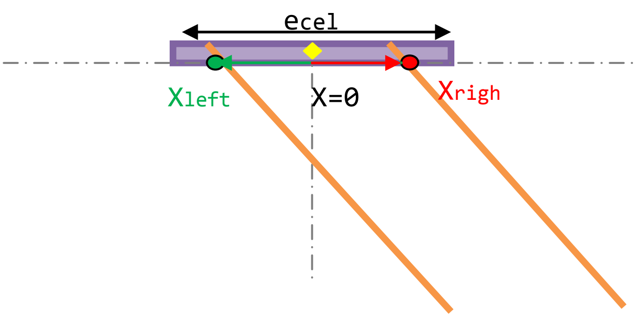


Figure 64 Ratio calculation with shadows. Case D

In this case the calculation of ratio has the same expression as in the original case but regarding that the crossing points have changed.

Equation 44

Case E

This case is splitted into two other cases since it corresponds to the situation in which none of the bounds hit the panel, that is, when the whole reflected area is out of the photovoltaic panel. The reflected area can be at the right or at the left hand side of the panel.

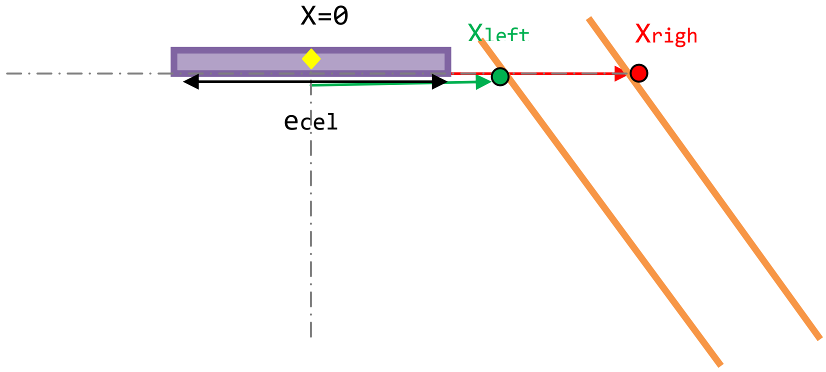


Figure 65 Ratio calculation with shadows. Case E1

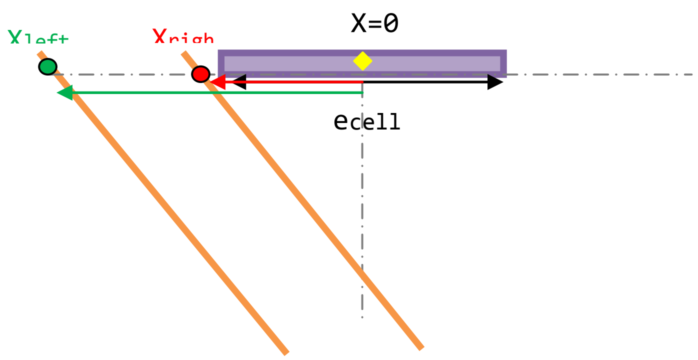


Figure 66 Ratio calculation with shadows. Case E2

For both cases shown in Figure 65 and Figure 66, the reflected area from the mirrors does not match in any point the panel so the ratio should be zero.

Equation 45

All the cases explained before (A, B, C , D and E) are inside the other possible situations, except in the case 2 in which the ratio remains the one computed before, without considering the shadows.

Equation 46

4.5.4. Evaluation of losses due to the shadows

Once the ratios have been computed for all the year, there is the need to know if the change in these values is important enough for the general behaviour and efficiency of the facility. If, as a whole, the variation of the ratios takes place early in the morning or late in the afternoon, when the solar irradiation is low, then the effect of the shadows will not be so important. But, if on the contrary, this variation is at midday, when irradiation is higher, and therefore, more amount of energy can be produced; the shadow effect would be significant enough to be considered in the future configuration of the prototype.

To do this part of the work, software developed in Matlab environment (program attached in Annex 2) was built based on the first program done so that the variation on the efficiency can be appreciated by the calculation of the ratios for all the year by fifteen-minute steps.

One way to compare the variation in the ratios, and besides, more realistic, is plotting the same graphics as it was done before to compare among them how the ratios have changed. Nevertheless, before showing them, it is convenient first to explain briefly the effect of the shadows in the ratio to understand in a better way the graphics. Because of the way in which the ratio has been defined, it is easily that its value changes drastically from zero to a great value. To explain the reason it is better to see a scheme.

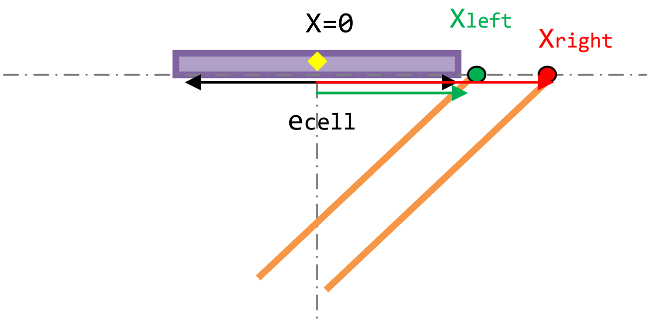


Figure 67 Changes in ratio value. Example of ratio=O

For the situation below, the shadows make the reflected light not to hit the panel at any point, for this reason, the ratio is null. But, as the sun rises along the morning, the shadow area is decreased, that is that the left hand side border begins to move inside the panel area, but at the beginning the hitting area from the mirror will be very low, so, the ratio will be very high.

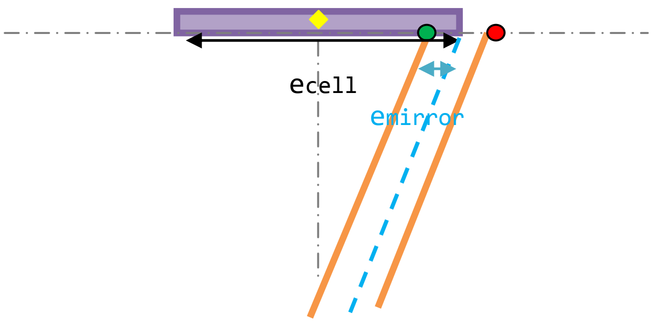


Figure 68Changes in ratio value. Example of ratio very high.

This is the particular situation, defined as case B, and the ratio, by Equation 42, is:

Equation 47

Since the width of the cell is considerably bigger than the mirror one, the ratio becomes huge when minutes ago its value was zero.

With this concept clear, the graphics for each mirror are shown now.

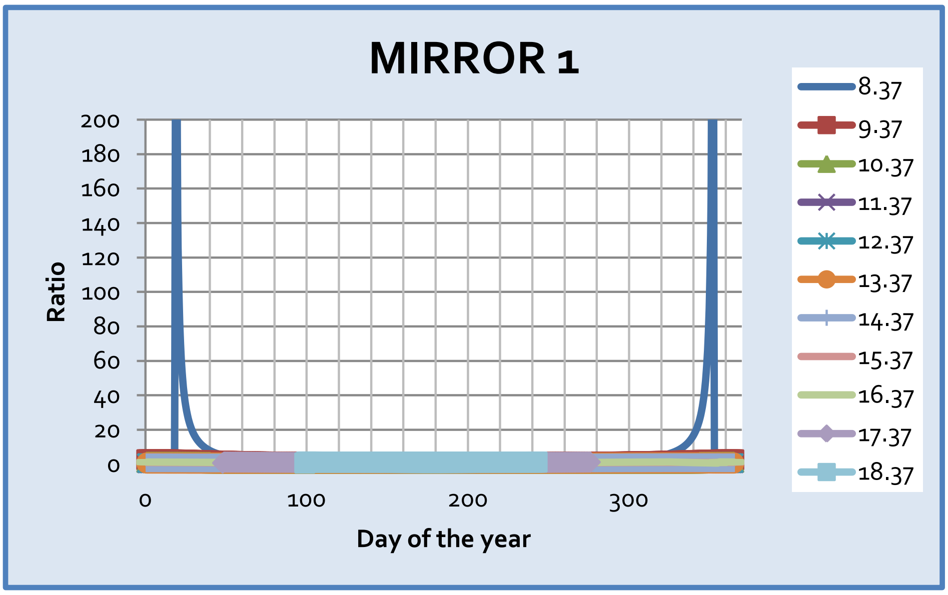


Figure 69 Ratio of mirror 1 along the year considering shadows.

As it can be seen, there are high values at 8:30 in the morning, far away from the rest of points. This is because the reason explained before. Since, it only happens at the first hour in the morning, and in days that belong to winter or autumn; the irradiation is not as high as it is in summer or at midday, it is possible to dispense with this curve to analyse better the general behaviour of the facility because the rest of the curves have lower values that cannot be analyse in this scale.

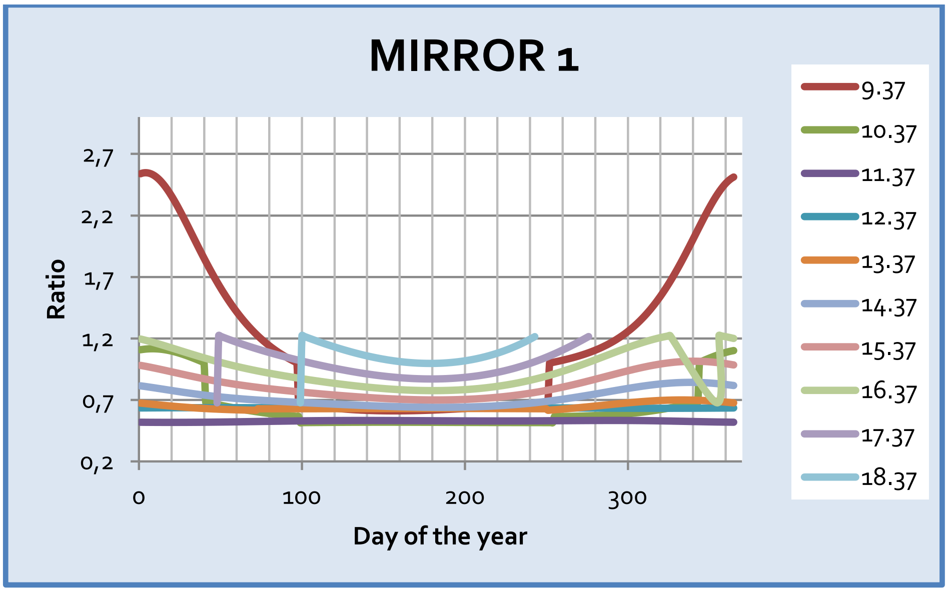


Figure 70 Ratio of mirror 1 along the year considering shadows. Zoom.

In this way, it is easier to compare the results with the previous graphics obtained in which the shadows were not taken into account. Comparing both, it is seen that the upper limit has risen considerably, not only for the curves in the early morning. As a whole, all the curves has been moved upwards and now, the mean value of the ratio for the whole year for the first mirror is around 0,97 when before it took the value of 0,52.It seems that the ratio has been improved but what is happening is that the cases in which it has increased a lot because of the small panel surface covered by the concentrated light are compensating the cases in which the ratio has dropped.

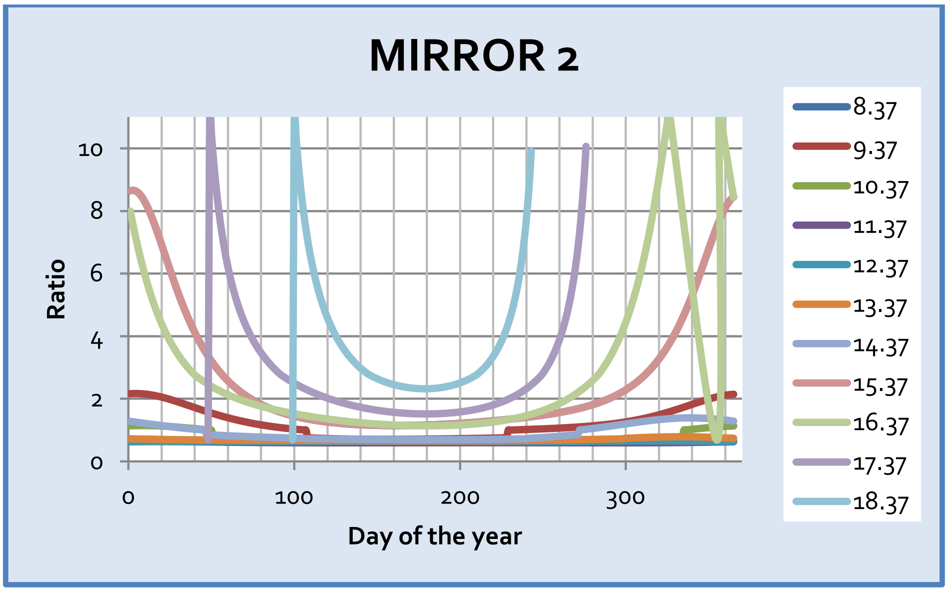


Figure 71 Ratio of mirror 2 along the year considering shadows.

In this case, more curves have changed their behavior but more significantly the ones early in the morning or late in the afternoon, whereas the rest remains more or less the same, although moved upwards achieving values greater than 1 and even than before. Since in this mirror the values do not jump as in mirror 1, there is no need to make a zoom at them.

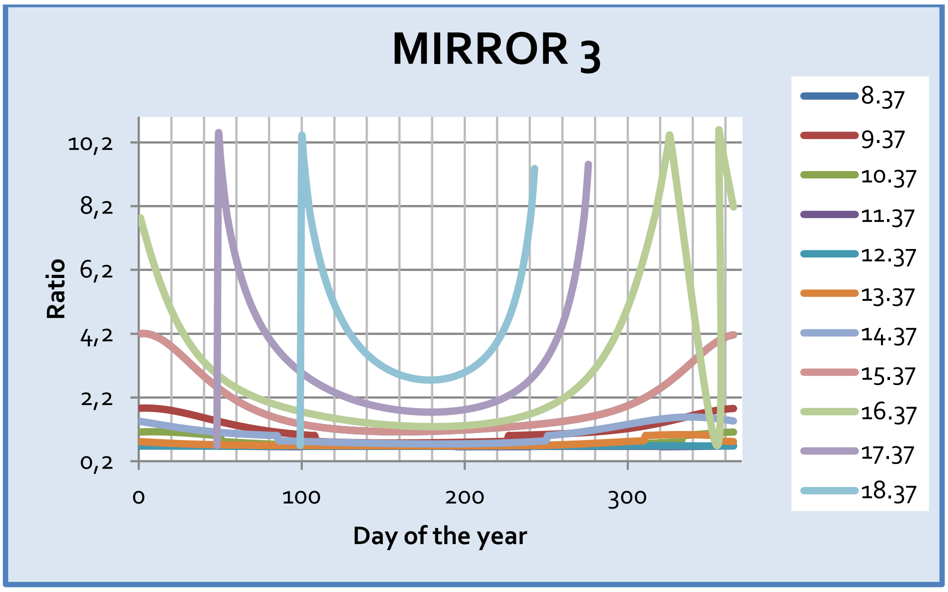


Figure 72 Ratio of mirror 3 along the year considering shadows.

Just as has happened before, the ratios has been increased but only in a meaningful way for the moments in which the irradiation is not such important.

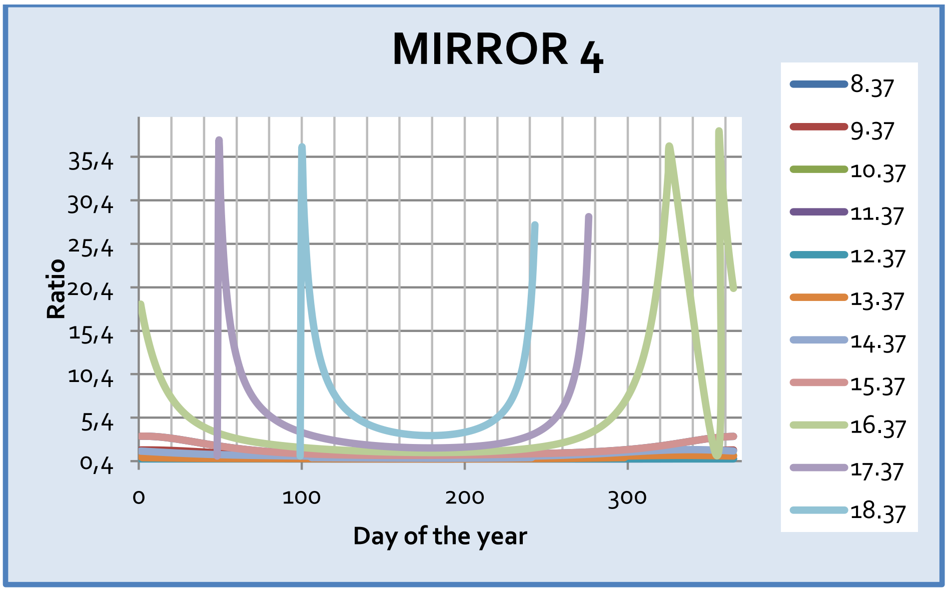


Figure 73 Ratio of mirror 4 along the year considering shadows.

As it has happened in the previous mirrors, for the fourth at late hours the ratios arise great values but the rest of the time the ratio remains more or less inside the general behaviour.

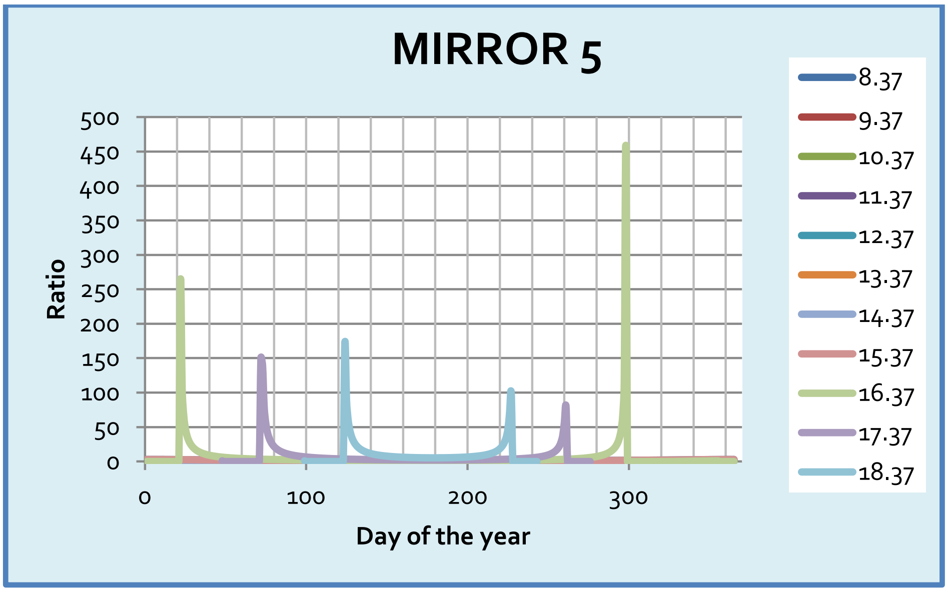


Figure 74 Ratio of mirror 5 along the year considering shadows.

For this mirror, as it happened with the first one, a zoom should be done in order to see better the general shape of the mirrors, ignoring the points that achieve values so high.

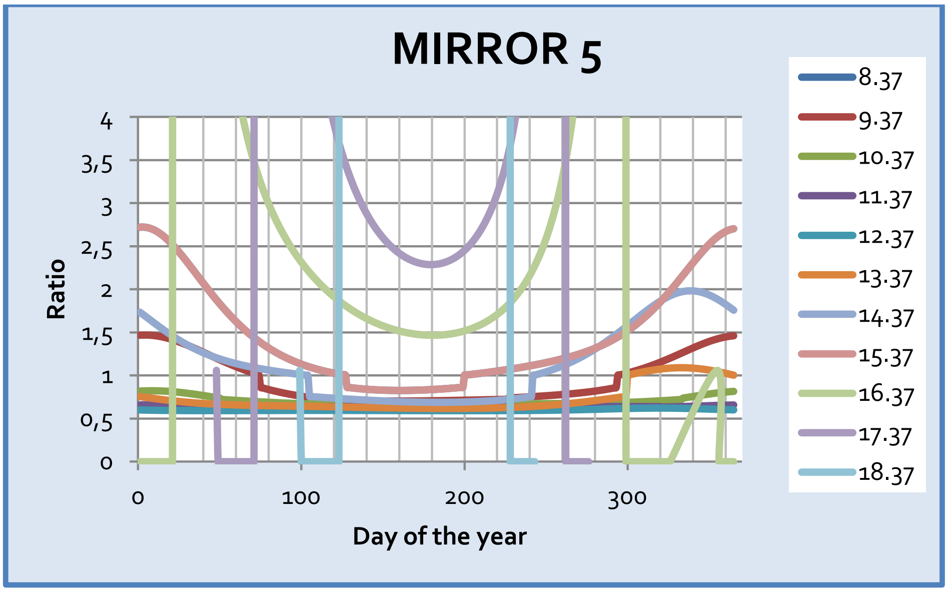


Figure 75 Ratio of mirror 5 along the year considering shadows. Zoom.

In this case, even for the hours at midday, the ratios have increased a lot so the losses due to the shadows can be important enough to be considered in future designs.

Some vertical lines are fast identified and seem weird but they are the ratio values that jump from zero to big values because of the fact explained before due to the ratio definition and the shadow behaviour along the day.

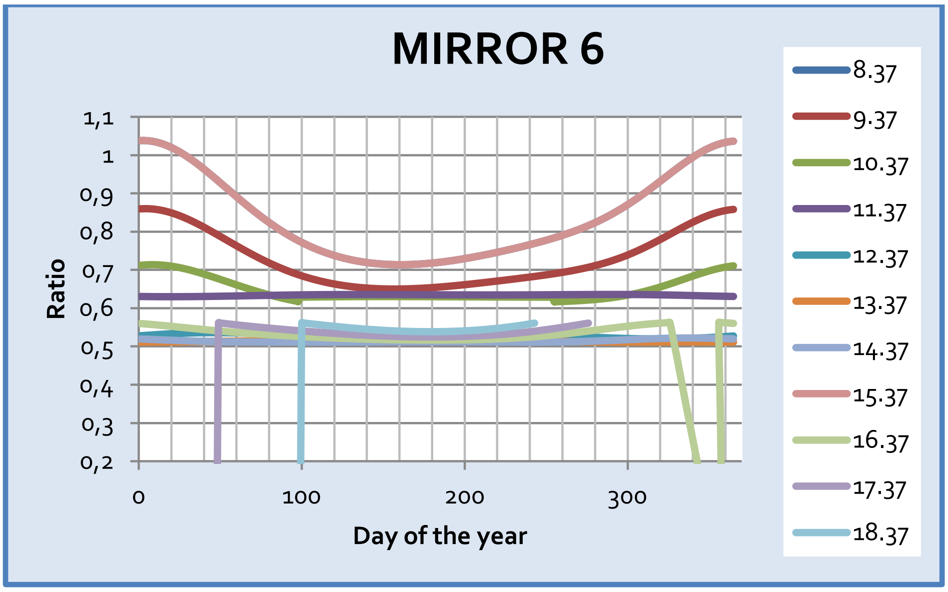


Figure 76 Ratio of mirror 6 along the year considering shadows.

For mirror 6, the curves have been moved upwards, increasing the mean value for the whole year. But, this increase is not as great as in the other cases.

As it was done in section 4.2.2, the total energy calculation is being calculated by means of the Matlab software implementation, but now, taking into consideration the shadows effect. In this way the working capacity of the installation can be compared. Since the ratio is being used in the energy equation as efficiency, the values greater than one, will increase it when actually, they limit the energetic capacity of the panel. So, with this study, the energy concentrated over the photovoltaic panel along the year found was:

Equation 48

Without considering the shadows in the problem, the obtained energy was ; which is a 60 % greater than the obtained here. This basically means that the shadow among the mirrors cannot be ignored in future improvements and designs for new prototype geometries.

The study of the losses due to the shadows has been done in order to evaluate if the losses due to this fact is so important to redesign the prototype in such a way that this effect was reduced. The way would be rectifying the rotating angle of the mirror in order to achieve a higher reflected area hitting the panel and reducing the number of ratios bigger than one.

In order to evaluate the efficiency of the concentration, by Matlab, the annual energy calculation for a flat photovoltaic panel with the same surface area as the mirrors has been calculated. The model developed for this last one case is the same as for the prototype, but considering its own characteristics. The same assumptions were taken for both of them.

Equation 49

The density of concentrated energy on the panel is presented now as a comparison to the flat panel in order to have an idea of the improvements on the results due to the implementation of the concentrator.

Equation 50

As it was obtained last year with the measurements, the concentrating capacity of the prototype, compared to a flat installation is 2.5 times bigger than a traditional panel. The ideal concentration is not the desired one, which would be 6 times.

Chapter 5

5. CONCLUSIONS AND FUTURE WORK

This chapter remarks the conclusions reached along the work and the future lines to address the issues raised.

5.1. Conclusions

In this present work it was developed an evaluation of the losses of a planar photovoltaic concentrator prototype of medium-low concentrating capacity. The first step has been the development of a mathematical model by which a ratio of the reflected sunlight by each mirror on the panel is achieved. Once this model was verified, a sort of variables that define the main configuration of the facility, were varied in order to analyse the possible attainable improvements.

Main conclusions extracted that will be explained are the main geometrical features that do not allow the prototype the desirable concentrating capacity.

- Results from the model:
    - The development and subsequent implementation of a geometrical model for the facility enables to analyse the working capacity of the prototype in a simple way.
    - By this approach it was concluded that ratios bigger than one are undesirable and less convenient than ratios smaller than one, since the electric current is limited by photovoltaic panel area not matched.

- Due to the geometrical configuration, the overall mean value for the ratio is about 0.75, which is not a bad value, considering the ratio meaning as a kind of efficiency of the reflected sunlight on the panel.
- It should be taken into consideration that this value is affected also by the values that are bigger than one, for this reason, it cannot be interpreted as a good performing value. Actually, as it is influenced by the values bigger than one, this means that the energy is being limited by these cases.
- By looking at the analysis of each mirror separately and their behaviour along the year for every hour along the day, we can realise that it is not that bad. At midday the ratios are always underneath one, so as these hours are the ones with the higher irradiation intensity of the day, the obtained results indicate that the prototype is working correctly in that sense.

- Variation of parameters:
    - Since it was decided that the panel width would be changed to a higher one, this analysis was carried out in order to compared to possible improvements or worsening of its working capacity due to this decision.
    - Increase the panel width, keeping the mirrors, increase the amount of ratios greater than one respect to the current geometry, so this configuration would not enhance the energy produced.
    - Fixing the panel width, the mirrors configuration was changed, decreasing their widths and therefore, increasing the gaps among them. This study leads to the conclusion that less ratios bigger than one is achieved but, on the other hand, the amount of energy reached is also lower. So, summarizing, some energy is sacrificed but a better working capacity of the facility is obtained, better general efficiency.
    - The next step in this part of the study was the analysis of the variation of the panel height respect to the mirrors. As it was expected at the beginning, the concentration capacity of the installation was been improved significantly by increasing this distance.
    - The last part consisted on the possible horizontal movement of the photovoltaic panel along its longitudinal axis in order to take advantage of the reflected area, not hitting the panel in the different seasons of the year. The possible limits of its movement were proposed.

- Shadows evaluation:
    - The last part of the work consisted on the study of the importance of the shadows in the general performance of the facility arriving to the conclusion that it does.
    - The development of a mathematical and geometrical model of the interaction among the mirrors along the year allowed building a Matlab program.
    - By the software implementation the total energy achieved along the year taking into consideration the shadows leads to the conclusion that they will have to be taken into account for future prototype designs.

- The total energy achieved considering the shadow interaction was a 66% lower than without including them in the study.

At the end of the project, the comparison between the current facility and a flat installation with the same surface area used was done. The result was that the concentrator achieves 2.5 times more energy than a simple installation built with flat panels. This is not the desired result; the ideal situation would have been 6 times because of the implementation of 6 mirrors. This was the result obtained in the measurements carried out last summer directly from the facility. So, as a summary, it can be said, that the results from the software developed are correct because they match with the real data collected.

5.2. Future work

In order to achieve a better performance on the concentrator prototype that has been studied on this project, future work should address the following tasks:

If the width of the panel is finally changed to a bigger one, the width of the mirrors should also be changed and as it is increased the total width of the structure would also be increased. But, on the other hand, if the panel remains the same, a reduction on the mirrors width could be done, increasing hence, the gap among them. With this action, a small quantity of energy will be lost but a better performance of the facility would be reached.

Also, as it was analysed, a small increase in the height of the photovoltaic panel respect to the mirrors increase the concentration capacity of them, so, this could be another step to follow in order to achieve a better result.

The movement of the photovoltaic panel along the year could be implemented. Although, an electronic tracking system may be expensive to the increase of energy provided, the movement can be done manually four times a year, one for each season. The improvement in the final energy obtained could be analysed.

Now, that it is known that the shadows are important in the working capacity of the installation, a study of the corrective angles for the mirrors should be carried out. This must be done in order to decrease the shadow area that does not allow the concentrated sunlight to hit the panel.

A parameter that should be studied is the cost of the energy of the installation. A ratio in which the cost of the facility (varying with the time), is compared to the total energy produced by it. Usually photovoltaic applications convenience is evaluated by this kind of economical variables that measure the cost per unit of energy produced. As it was done, this ratio could be also obtained for a flat installation in order to compare the results.

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ANNEXES

Annex 1. Matlab program. Computation of the ratios and annual energy

```
close all
clear all

%placement information
lat_gradi=42;
lat_primi=33;
lat_rad=((lat_gradi+lat_primi/60)*3.14/180);
long_gradi=12;
long_primi=27;
long_rif=15;
long_oss=long_gradi+long_primi/60;
%length of the mirrors(m)
ls=6.355;
%width of the mirrors(m)
es=0.29;
%width of the cell(m)
ec=0.55;


%Now we define the energy at the begining as zero.
Energy(1:6)=0;
ENERGY=0;
step=0; %step is a counter that allows us to run along the data-matrix
in columns
%we do everything for everyday of the year
for g=1:365

delta=23.45*pi/180*sin(2*pi*(284+g)/365);
E=-10.1*sin(2*pi*(2*g+31)/366)-6.9*sin(2*pi*g/366);

B=[1.0025 0.6025 0.2025 0.2025 0.6075 1.0075];
 h=1.165;

    for i=1:3
      c(i)=pi-atan(h/B(i));
      c(i+3)=atan(h/B(i+3));
    end



% we run the program for everyhour of the day, from 5 AM in the morning
% until 7 PM in the evening
for ora=5:19
        for min= 7:15:52
          step=step+1 ;
        ora_conv=ora+min/60;
        ora_solare=ora_conv+(E-4*(long_rif-long_oss))/60;
        omega=(-15*3.14/180*ora_solare)+3.14;
        %calculation of alfa_yz

alfa=asin(cos(lat_rad)*cos(delta)*cos(omega)+sin(delta)*sin(lat_rad));
```

```
            if(cos(alfa)~=0)
             gamma_=acos((sin(alfa)*sin(lat_rad)-
sin(delta))/(cos(alfa)*cos(lat_rad))); %azimut
            else
             gamma_=0;
            end
            if(ora_solare>12)
            gamma_=-gamma_;
            end
            alfa_yz=atan(tan(alfa)/sin(gamma_));
            if(alfa>0)
            if (alfa_yz<0)
            alfa_yz=alfa_yz+pi;
            end
            else
            alfa_yz=0;
            end
%in order to calculate the ratio, we need the c angle in such a way that
we
%have simmetry .

B=[1.0025 0.6025 0.2025 0.2025 0.6075 1.0075];
 h=1.165;

    for i=1:6
      c_(i)=atan(h/B(i));
    end

    if alfa>0
        for i=1:3
            %in the morning
        if ora_solare<12

                %for mirrors 1, 2 and 3
                 ratio(i)=ec.*sin(c_(i))./(es.*cos(-alfa_yz/2+c_(i)/2));

                 %for mirrors 4,5,6
                 ratio(i+3)=(ec.*sin(c_(i+3)))./(es.*cos(pi/2-c_(i+3)/2-
alfa_yz/2));
             %in the afternoon
        elseif ora_solare>12

                 %for mirrors 1, 2 and 3
                 ratio(i)=(ec.*sin(c_(i)))./(es.*(cos(-
c_(i)/2+alfa_yz/2)));
                 %for mirrors 4,5,6

ratio(i+3)=(ec.*sin(c_(i+3)))./(es.*cos(c_(i+3)/2+alfa_yz/2-pi/2));
        end
        end
                 %now we fill the matrix A in the following way:

% day|hour |minute|ratio mirror1 |ratio mirror2|ratio mirror3|
ratio mirror 4|ratio mirror 5|ratio mirror6|

                     A(step,1)=g;
                     A(step,2)=ora;
                     A(step,3)=min;
                     A(step,4)=ratio(1);
                     A(step,5)=ratio(2);
```

```
                    A(step,6)=ratio(3);
                    A(step,7)=ratio(4);
                    A(step,8)=ratio(5);
                    A(step,9)=ratio(6);



    elseif alfa<0
% if alfa<0 is like the sun comes from behind the horizon, this means
that
% there is not any sunlight, it is still darkness, so, there is not any
% ratio.

step=step-1;
if step==0
    step=1;
end




%          A(step,1)=g;
%          A(step,2)=ora;
%          A(step,3)=min;
%          A(step,4)=0;
%          A(step,5)=0;
%          A(step,6)=0;
%          A(step,7)=0;
%          A(step,8)=0;
%          A(step,9)=0;

    end


    % A: extraatmospherical radiation, outside the atmosphere
    Arad=1150.65 +72.43*cos(0.95*g*pi/180)
+34.25*sin(0.017*g*pi/180)+1.5*log(g);
    % B: reduction of the radiation caused by the atmosphere
    B=1/(6.74+0.026*g-5.13*10^(-4)*g^2+2.24*10^(-6)*g^3-2.8*10^(-
9)*g^4);
    %Now we have a value that changes for every mirror




        end
end

end




for g=1:365
    for ora=5:19
    min=0;

    for k=1:6
        for i=1:length(A)
            if alfa>0
```

```
            x(k)=abs((alfa_yz-c(k))/2);
            elseif alfa<=0
            x(k)=0;
            end

        psis_=-pi/2; %for the first three mirrors
        if ora_solare<=12 % in the morning
            psis(k)=psis_;
        elseif ora_solare>12  %in the afternoon
            psis(k)=-psis_;
        end


        teta(k)=acos(cos(alfa).*cos(gamma_-
psis(k)).*sin(x(k))+sin(alfa).*cos(x(k)));

        %in order not to have a value of ID negative, we put this
        %condition.



       % IDn: intensity of the normal direct radiation to the surface
        IDn=Arad./(exp(B./sin(alfa)));
        %ID:intensity of the direct radiation(W/m^2)
        ID(k)=IDn.*abs(cos(teta(k)));
        %Now we have to multiply ID times the surface area and the
ratio.

        Power(k)=ID(k).*ls.*es.*A(i,k+3);
        Energy(k)=Energy(k)+Power(k).*3600;

 end
    end
    end
end



 for k=1:6
 ENERGY=ENERGY+Energy(k);
 end
 ENERGY
```

Annex 2. Matlab program. Computation of the ratios and annual energy. Shadows evaluation.

```
close all
clear all

%placement information
lat_gradi=42;
lat_primi=33;
lat_rad=((lat_gradi+lat_primi/60)*3.14/180);
long_gradi=12;
long_primi=27;
long_rif=15;
long_oss=long_gradi+long_primi/60;
%length of the mirrors(m)
ls=6.355;
%width of the mirrors(m)
es=0.39;
%width of the cell(m)
ec=0.263;
%gap between mirrors
s=0.01;


%Now we define the energy at the begining as zero.
Energy(1:6)=0;
ENERGY=0;

step=0; %step is a counter that allows us to run along the data-matrix
in columns
%we do everything for everyday of the year
for g=1:365

delta=23.45*pi/180*sin(2*pi*(284+g)/365);
E=-10.1*sin(2*pi*(2*g+31)/366)-6.9*sin(2*pi*g/366);

B=[1.0025 0.6025 0.2025 0.2025 0.6025 1.0025];
 h=1.165;

    for i=1:3
      c(i)=pi-atan(h/B(i));
      c(i+3)=atan(h/B(i+3));
    end



% we run the program for everyhour of the day, from 5 AM in the morning
% until 7 PM in the evening
for ora=6:19
        for min= 7:15:52
          step=step+1 ;
        ora_conv=ora+min/60;
        ora_solare=ora_conv+(E-4*(long_rif-long_oss))/60;
        omega=(-15*3.14/180*ora_solare)+3.14;
        %calculation of alfa_yz
```

```
alfa=asin(cos(lat_rad)*cos(delta)*cos(omega)+sin(delta)*sin(lat_rad));
           if(cos(alfa)~=0)
            gamma_=acos((sin(alfa)*sin(lat_rad)-
sin(delta))/(cos(alfa)*cos(lat_rad))); %azimut
           else
            gamma_=0;
           end
           if(ora_solare>12)
           gamma_=-gamma_;
           end
           alfa_yz=atan(tan(alfa)/sin(gamma_));
           if(alfa>0)
           if (alfa_yz<0)
           alfa_yz=alfa_yz+pi;
           end
           else
           alfa_yz=0;
           end
%in order to calculate the ratio, we need the c angle in such a way that
we
%have simmetry .

B=[1.0025 0.6025 0.2025 0.2025 0.6025 1.0025];
 h=1.165;

    for i=1:6
      c_(i)=atan(h/B(i));
      x(i)=(alfa_yz-c(i))/2;
    end
    ratio(1:6)=0;
    if alfa_yz>0
        for i=1:3
            %in the morning
        if ora_solare<12
            alfa_prima=pi-alfa;
               %for mirrors 1, 2 and 3
                ratio(i)=ec.*sin(c_(i))./(es.*cos(-alfa_yz/2+c_(i)/2));
%                 if ratio(i)>=1.05
%                     ratio(i)=1;
%                 end
                %for mirrors 4,5,6
                ratio(i+3)=(ec.*sin(c_(i+3)))./(es.*cos(pi/2-c_(i+3)/2-
alfa_yz/2));
%                 if ratio(i+3)>=1.05
%                     ratio(i+3)=1;
%                 end
             %in the afternoon
        elseif ora_solare>12

                %for mirrors 1, 2 and 3
                 ratio(i)=(ec.*sin(c_(i)))./(es.*(cos(-
c_(i)/2+alfa_yz/2)));
%                 if ratio(i)>=1.05
%                     ratio(i)=1;
%                 end

                %for mirrors 4,5,6

ratio(i+3)=(ec.*sin(c_(i+3)))./(es.*cos(c_(i+3)/2+alfa_yz/2-pi/2));
```

```
%                 if ratio(i+3)>=1.05
%                     ratio(i+3)=1;
%                 end

        end
        end
                %now we fill the matrix A in the following way:

%   day|hour |minute|ratio mirror1 |ratio mirror2|ratio mirror3|ratio
mirror 4|ratio mirror 5|ratio mirror6|

                    A(step,1)=g;
                    A(step,2)=ora;
                    A(step,3)=min;
                    A(step,4)=ratio(1);
                    A(step,5)=ratio(2);
                    A(step,6)=ratio(3);
                    A(step,7)=ratio(4);
                    A(step,8)=ratio(5);
                    A(step,9)=ratio(6);


    elseif alfa<0
% if alfa<0 is like the sun comes from behind the horizon, this means
that
% there is not any sunlight, it is still darkness, so, there is not any
% ratio.

step=step-1;
if step==0
    step=1;
end



%          A(step,1)=g;
%          A(step,2)=ora;
%          A(step,3)=min;
%          A(step,4)=0;
%          A(step,5)=0;
%          A(step,6)=0;
%          A(step,7)=0;
%          A(step,8)=0;
%          A(step,9)=0;

    end



    %_____________________MORNING_______________________

ratio_(1:6)=0;

   for t=1:5
   %if alfa_yz>0
    if ora_solare<12

        %CASE 1
```

```
    if x(t)<0
        if x(t+1)<0

            %first we calculate the angles and the coordinates of the
            %interesting points
            beta(t+1)= -tan(alfa_yz)*(((t+1)-7/2)*(s+es)-
es/2*cos(x(t+1)))-es/2*sin(x(t+1));
            gamma(t)=-tan(pi-abs(x(t)))*((t-7/2)*(s+es));
            xp(t)=(gamma(t)-beta(t+1))/(tan(alfa_yz)-tan(pi-abs(x(t))));
            yp(t)=tan(alfa_yz)*xp(t)+beta(t+1);
            xe(t)=(t-7/2)*(s+es)-es/2*cos(x(t));
            ye(t)=-es/2*sin(x(t));
            x_ph(t)=(h+xp(t)*tan(pi-c(t))-yp(t))/(tan(pi-c(t)));

            x_eh(t)=(h+xe(t)*tan(pi-c(t))-ye(t))/(tan(pi-c(t)));

            %Case A
            if x_ph(t)>ec/2
                if x_eh(t)<-ec/2
                    ratio_(t)=ec/(abs(x_ph(t)-x_eh(t)));
                end
            end
            %Case B
            if x_ph(t)<ec/2
                if x_eh(t)<-ec/2
                     ratio_(t)=ec/(abs(ec/2+x_ph(t)));
                end
            end
            %case C
            if x_ph(t)>ec/2
                if x_eh(t)>-ec/2
                     ratio_(t)=ec/(abs(ec/2-x_eh(t)));
                end
            end
            %Case D
            if x_ph(t)<ec/2
                if x_eh(t)>-ec/2
                     ratio_(t)=ec/(abs(x_ph(t)-x_eh(t)));
                end
            end
            %Case F
          if x_ph(t)>ec/2
                if x_eh(t)>ec/2
                    ratio_(t)=0;
                end
          end
          if x_ph(t)<-ec/2
                if x_eh(t)<-ec/2
                    ratio_(t)=0;
                end
          end

        end
    end



          %CASE 2
           if x(t)>0
              if x(t-1)<0
                  ratio_(t)=ratio(t);
```

```
                ratio_(t-1)=ratio(t-1);
            end
         end
          %CASE 2b
         if x(t)<0
            if x(t+1)>0
                ratio_(t)=ratio(t);
                ratio_(t+1)=ratio(t+1);
            end
         end
  end
 %end
 end
 ratio_(6)=ratio(6);

%if alfa_yz>0
if ora_solare<12
  for t=2:6
         %CASE 3
         if x(t)>0
                if x(t-1)>0
                %first we calculate the angles and the coordinates
          xf(t)=(t-7/2)*(s+es)+es/2*cos(x(t));
          yf(t)=es/2*sin(x(t));
          xf(t-1)=(t-1-7/2)*(s+es)+es/2*cos(x(t-1));
          yf(t-1)=es/2*sin(x(t-1));
          omega(t-1)=-tan(pi-c(t))*xf(t-1)+es/2*sin(abs(x(t-1)));
          omega(t)=-tan(pi-c(t))*xf(t)+es/2*sin(x(t));
          x_fh(t-1)=(h-omega(t-1))/tan(pi-c(t));
          x_fh(t)=(h-omega(t))/tan(pi-c(t));



            %Case A
          if x_fh(t)>ec/2
              if x_fh(t-1)<-ec/2
                  ratio_(t)=ec/(abs(x_fh(t)-x_fh(t-1)));
              end
          end
          %Case B
          if x_fh(t)<ec/2
              if x_fh(t-1)>-ec/2
                  ratio_(t)=ec/(abs(x_fh(t)-x_fh(t-1)));
              end
          end
          %Case C
          if x_fh(t)>ec/2
              if x_fh(t-1)>-ec/2
                  ratio_(t)=ec/(abs(ec/2-x_fh(t-1)));
              end
          end
          %Case D
          if x_fh(t)<ec/2
              if x_fh(t-1)<-ec/2
                  ratio_(t)=ec/(abs(x_fh(t-1)+ec/2));
              end
          end
          %Case F
        if x_fh(t)>ec/2
              if x_fh(t-1)>ec/2
                  ratio_(t)=0;
```

```
                end
          end
          if x_fh(t)<-ec/2
                if x_fh(t-1)<-ec/2
                    ratio_(t)=0;
                end

          end
          ratio_(1)=ratio(1);
                  end
           end
   end

   %Now we build the new ratio matrix

                    C(step,1)=g;
                    C(step,2)=ora;
                    C(step,3)=min;
                    C(step,4)=ratio_(1);
                    C(step,5)=ratio_(2);
                    C(step,6)=ratio_(3);
                    C(step,7)=ratio_(4);
                    C(step,8)=ratio_(5);
                    C(step,9)=ratio_(6);

 end
 %end




% ____________________AFTERNOON___________________:

for t=2:6
%if alfa_yz>0
    if ora_solare>12


        %CASE 1 and 3
        if x(t)>0
           if x(t-1)>0

        %first we calculate the angles and the coordinates of the case 1
        xf(t)= (t-7/2)*(s+es)+es/2*cos(abs(x(t)));
        yf(t)= es/2*sin(abs(x(t)));
        xf(t-1)=(t-1-7/2)*(s+es)+es/2*cos(abs(x(t-1)));
        yf(t-1)=es/2*sin(abs(x(t-1)));
        %Now we calculate the constants
        beta(t-1)=-tan(alfa_yz)*xf(t-1)+yf(t-1);
        gamma(t)=-tan(x(t))*(t-7/2)*(s+es);
        %point P, in case 1
        xp(t)=(gamma(t)-beta(t-1))/(tan(alfa_yz)-tan(abs(x(t))));
        yp(t)=tan(alfa_yz)*xp(t)+beta(t-1);

        % for the case 3, the constants
        nu(t-1)=-tan(pi-c(t))*xf(t-1)+yf(t-1);
        nu(t)=-tan(pi-c(t))*xf(t)+yf(t);
```

```
% point G, in case 3
xg(t)=(gamma(t)-nu(t-1))/(tan(pi-c(t-1))-tan(abs(x(t))));

% Now we put the condition in order to know if the effect of the
% shadow is bigger than the effect of the interference om the
% reflected area of the mirror,
 %CASE 1

if xp(t)>xg(t)
    %crossing points with the panel (y=h)
x_ph(t)=(h+tan(pi-c(t))*xp(t)-yp(t))/(tan(pi-c(t)));
x_fh(t)=(h+tan(pi-c(t))*xf(t)-yf(t))/(tan(pi-c(t)));

    %calculation of the ratios depending on the case

    %Case A
    if x_fh(t)>ec/2
        if x_ph(t)<-ec/2
            ratio_(t)=ec/(abs(x_fh(t)-x_ph(t)));
        end
    end

    %Case B
    if x_fh(t)>ec/2
        if x_ph(t)>-ec/2
            ratio_(t)=ec/(abs(ec/2-x_ph(t)));
        end
    end
   %Case C
   if x_fh(t)<ec/2
        if x_ph(t)<-ec/2
            ratio_(t)=ec/(abs(ec/2+x_fh(t)));
        end
   end
    %Case D
    if x_fh(t)<ec/2
        if x_ph(t)>-ec/2
            ratio_(t)=ec/(abs(x_fh(t)-x_ph(t)));
        end
    end
    %Case E
    if x_ph(t)>ec/2
           if x_fh(t)>ec/2
               ratio_(t)=0;
            end
      end
      if x_ph(t)<-ec/2
            if x_fh(t)<-ec/2
               ratio_(t)=0;
            end
      end
      %now we check the condition of CASE 3, in which the
     %interference of the mirror is more important than the
    shadow created.

elseif xg(t)>xp(t)
    %CASE 3
  %crossing points at y=h
x_fh(t-1)=(h-nu(t-1))/tan(pi-c(t));
x_fh(t)=(h-nu(t))/tan(pi-c(t));
```

```
            %Case A
            if x_fh(t)>ec/2
                if x_fh(t-1)<-ec/2
                    ratio_(t)=ec/(abs(x_fh(t)-x_fh(t-1)));
                end
            end
            %Case B
            if x_fh(t)>ec/2
                if x_fh(t-1)>-ec/2
                    ratio_(t)=ec/(abs(ec/2-x_fh(t-1)));
                end
            end
            %Case C
            if x_fh(t)<ec/2
                if x_fh(t-1)<-ec/2
                    ratio_(t)=ec/(abs(ec/2+x_fh(t)));
                end
            end
            %Case D
            if x_fh(t)<ec/2
                if x_fh(t-1)>-ec/2
                    ratio_(t)=ec/abs((x_fh(t)-x_fh(t-1)));
                end
            end

             %Case E
          if x_fh(t)>ec/2
                 if x_fh(t-1)>ec/2
                      ratio_(t)=0;
                  end
            end
            if x_fh(t)<-ec/2
                  if x_fh(t-1)<-ec/2
                      ratio_(t)=0;
                  end
            end


              end
             end
             end



             %CASE 2
             if x(t)>0
                if x(t-1)<0
                    ratio_(t)=ratio(t);
                    ratio_(t-1)=ratio(t-1);
                end
             end

             ratio_(1)=ratio(1);
    end
end

%end
```

```
for t=1:5
  %if alfa_yz>0
  if ora_solare>12

  %CASE 4
  if x(t)<0
      if x(t+1)<0
  %points and constants
  xe(t)=(t-7/2)*(s+es)-es/2*cos(abs(x(t)));
  ye(t)=es/2*sin(abs(x(t)));
  xe(t+1)=(t+1-7/2)*(s+es)-es/2*cos(abs(x(t+1)));
  ye(t+1)=es/2*sin(abs(x(t+1)));
  tetta(t)=-tan(pi-c(t))*xe(t)+ye(t);
  tetta(t+1)=-tan(pi-c(t))*xe(t+1)+ye(t+1);
  %crossing points with the panel
  x_eh(t)=(h-tetta(t))/tan(pi-c(t));
  x_eh(t+1)=(h-tetta(t+1))/tan(pi-c(t));

  %Case A
  if x_eh(t+1)>ec/2
      if x_eh(t)<-ec/2
          ratio_(t)=ec/abs(x_eh(t+1)-x_eh(t));
      end
  end
  %Case B
  if x_eh(t+1)>ec/2
      if x_eh(t)>-ec/2
          ratio_(t)=ec/abs(ec/2-x_eh(t));
      end
  end
  %Case C
  if x_eh(t+1)<ec/2
      if x_eh(t)<-ec/2
          ratio_(t)=ec/abs(ec/2+x_eh(t+1));
      end
  end
  %Case D
  if x_eh(t+1)<ec/2
      if x_eh(t)>-ec/2
          ratio_(t)=ec/abs(x_eh(t+1)-x_eh(t));
      end
  end
  %Case E
  if x_eh(t+1)>ec/2
      if x_eh(t)>ec/2
          ratio_(t)=0;
      end
  end
  if x_eh(t+1)<-ec/2
      if x_eh(t)<-ec/2
          ratio_(t)=0;
      end
  end


      end
  end
   ratio_(6)=ratio(6);
  end

end
```

```
      %end
                    C(step,1)=g;
                    C(step,2)=ora;
                    C(step,3)=min;
                    C(step,4)=ratio_(1);
                    C(step,5)=ratio_(2);
                    C(step,6)=ratio_(3);
                    C(step,7)=ratio_(4);
                    C(step,8)=ratio_(5);
                    C(step,9)=ratio_(6);

     % ____CALCULATION OF THE TOTAL ENERGY:_______


    % A: extraatmospherical radiation, outside the atmosphere
    Arad=1150.65
+72.43*cos(0.95*g*pi/180)+34.25*sin(0.017*g*pi/180)+1.5*log(g);
    % B: reduction of the radiation caused by the atmosphere
    B=1/(6.74+0.026*g-5.13*10^(-4)*g^2+2.24*10^(-6)*g^3-2.8*10^(-
9)*g^4);
    %Now we have a value that changes for every mirror


end
end
end



for g=1:365
    for ora=5:19
    min=0;

    for k=1:6
        for i=1:length(C)
            if alfa>0
            x(k)=abs((alfa_yz-c(k))/2);
            elseif alfa<=0
            x(k)=0;
            end

        psis_=-pi/2; %for the first three mirrors
        if ora_solare<=12 % in the morning
            psis(k)=psis_;
        elseif ora_solare>12  %in the afternoon
            psis(k)=-psis_;
        end


        teta(k)=acos(cos(alfa).*cos(gamma_-
psis(k)).*sin(x(k))+sin(alfa).*cos(x(k)));

        %in order not to have a value of ID negative, we put this
        %condition.


      % IDn: intensity of the normal direct radiation to the surface
```

```
        IDn=Arad./(exp(B./sin(alfa)));
        %ID:intensity of the direct radiation(W/m^2)
        ID(k)=IDn.*abs(cos(teta(k)));
        %Now we have to multiply ID times the surface area and the
ratio.
        if C(i,k+3)<1
        Power(k)=ID(k).*ls.*es.*C(i,k+3);
        elseif C(i,k+3)>1
            if C(i,k+3)<2
            Power(k)=ID(k).*ls.*es;
            elseif C(i,k+3)>=2
            Power(k)=0;
            end
        end

        Energy(k)=Energy(k)+Power(k).*3600;

 end
    end
    end
end


 for k=1:6
 ENERGY=ENERGY+Energy(k);
 end
 ENERGY
```